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Note if anything has been removed from thesis.

Figure 2.1 p8, Figure 2.2 p9, Figure 2.3 p11, and pages 132-135

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**Design of an Energy Efficient Geographic Routing Protocol
for Mobile Ad-hoc Networks**

by

Hui Cao

**School of Technology
Oxford Brookes University**

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List of Symbols and Abbreviations

ABR	Associativity-Based Routing
AODV	Ad-hoc On-Demand Distance Vector routing protocol
AP	Access Point
BER	Bit Error Rate
BPSK	Binary Phase-Shift Keying
CCK	Complementary Code Keying
CGSR	Clusterhead-Gateway Switch Routing
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear To Send
DBPSK	Differential Binary Phase-Shift Keying
DCF	Distributed Coordination Function
DQPSK	Differential Quadrature Phase-Shift Keying
DREAM	Distance Routing Effect Algorithm for Mobility
DSR	Dynamic Source Routing protocol
DSSS	Direct-Sequence Spread Spectrum
EE-GRP	Energy Efficient Geographic Routing Protocol
EEE-GRP	Enhanced Energy Efficient Geographic Routing Protocol
ETSI	the European Telecommunications Standards Institute
FSLs	Fuzzy Sighted Link State routing
FSM	Finite State Machine
FSPL	Free Space Path Loss
FSR	Fisheye State Routing
FTP	File Transfer Protocol
GEDIR	Geographical Distance Routing
GeoCast	Geographic Addressing and Routing
GFG	Greedy-Face-Greedy
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
GRP	Geographic Routing Protocol

HIPERLAN	High-Performance radio LAN
HSR	Hierarchical State Routing
HTTP	Hypertext Transfer Protocol
ID	Identity
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical
LAN	Local Area Network
LANMAR	Landmark Ad-hoc routing protocol
LAR	Location-Aided Routing
LMR	Lightweight Mobile Routing
IP	Internet Protocol
MAC	Medium Access Control
MANET	Mobile Ad-hoc Networks
Mbps	Megabits per second
MIT	Massachusetts Institute of Technology
MFR	Most Forwarding within Radius
MPR	Multipoint Relay
NFP	Nearest with Forward Progress
Non-FSPL	Non Free Space Path Loss
ODF	Optimal-Distance Forwarding
OFDM	Orthogonal Frequency-Division Multiplexing
OLSR	Optimized Link State Routing
OUI	Organizationally Unique Identifier
PDA	Personal Digital Assistant
PHY	Physical layer
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RFC	Request for Comments
RREP	Route Reply control message
RREQ	Route Request control message
RERR	Route Error control message
RTS	Request To Send

Rx	Receiver
STD	State Transition Diagram
SNR	Signal-to-Noise Ratio
TBRPF	Topology Broadcast based on Reverse Path Forwarding
TC	Topology Control
TCP	Transmission Control Protocol
TORA	Temporally-Ordered Routing Algorithms
Tx	Transmitter
UDP	User Datagram Protocol
W	Watt
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
ZRP	Zone Routing Protocol

Abstract

Mobile Ad-hoc networks extend communications beyond the limit of infrastructure-based networks. Future wireless applications will take advantage of rapidly deployable, self-configuring multi-hop mobile Ad-hoc networks. In order to provide robust performance in mobile Ad-hoc networks and hence cope with dynamic path loss conditions, it is apparent that research and development of energy efficient geographic routing protocols is of great importance. Therefore various mobile Ad-hoc routing protocols have been studied for their different approaches. Forwarding strategies for geographic routing protocols are discussed and there is a particular focus on the path loss model used by those routing protocols, the restriction and disadvantage of using such path loss model is then discussed.

A novel geographic routing protocol which incorporates both the link quality and relay node location information has been developed to determine an energy efficient route from source to destination. The concepts of a gain region and a relay region to minimize the energy consumption have been proposed to define the area in where the candidate relay nodes will be selected with the minimized hop count. The signalling overhead required by the protocol has been analyzed in various scenarios with different traffic load, node densities and network sizes. Discrete event simulation models are therefore developed to capture the behaviour and characteristics of the operation of the developed routing protocol under different path loss conditions and network scenarios. A non-free space path loss model has been developed with a random loss between the nodes to simulate a realistic path loss scenario in the network. An enhanced signalling process has been designed in order to achieve advanced routing information exchange and assist routing determination.

Comparison of simulated characteristics demonstrates the significant improvement of the new routing protocol because of its novel features, the gain region to ensure the deduction of the energy consumption, the relay region to ensure the forward progress to the destination and hence maintain an optimised hop count. The simulation results showed that the energy consumption under the operation of the developed protocol is 30% of that with a conventional geographical routing protocol.

Chapter 1 Introduction

1.1 Overview

Wireless networks utilise two main architectures: infrastructure (single-hop) networks and mobile Ad-hoc (multi-hop) networks (MANETs) [1]. The general form both these architectures is illustrated in Figure 1.1.

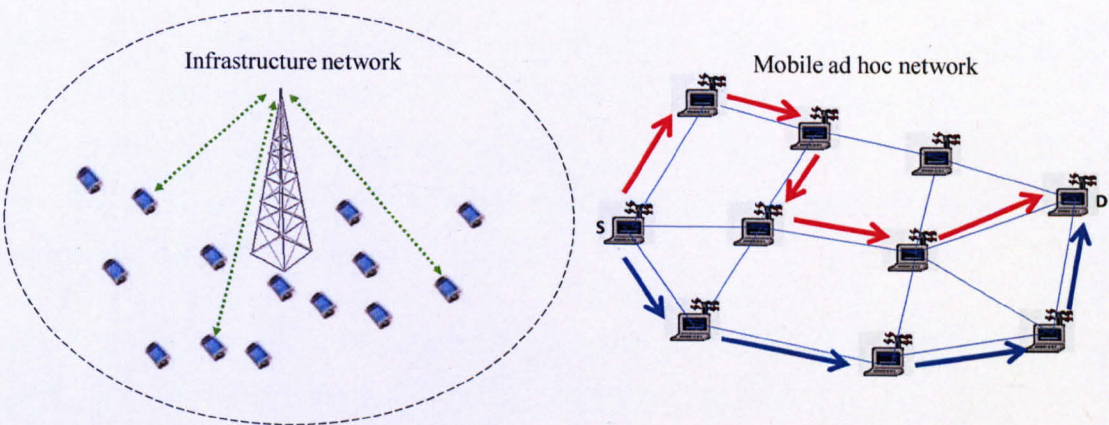


Figure 1.1 General structure of the wireless networks

A mobile Ad-hoc network is a network based on a set of autonomous nodes. There is no fixed infrastructure or a central server. All the nodes in the network act as routers to discover and maintain routes to other nodes. Wireless networks running in Ad-hoc mode offer more flexibility than infrastructure mode networks and eliminate single points of failure for the entire network. Ad-hoc networks [2-4] exclude the use of a wired infrastructure. A significant advantage of Ad-hoc networks is that mobile nodes can form arbitrary networks “on the fly” to exchange information without the need of a pre-existing network infrastructure. Mobile Ad-hoc networks can extend communication beyond the limit of infrastructure-based networks. Future wireless applications will take advantage of rapidly deployable, self-configuring multi-hop mobile Ad-hoc networks.

Currently mobile Ad-hoc networks are utilised and proposed for various applications such as wireless sensor networks (WSN) which are networks of many individual nodes,

each of which performs computations autonomously on data gathered via on-board sensors (optical, aural, temperature, etc.) or received via a wireless link.

Wireless networks of sensors are likely to be widely deployed in the near future because they greatly extend our ability to monitor and control the physical environment from remote locations and improve the accuracy of information obtained via collaboration among sensor nodes and online information processing at those nodes. Networking these sensors (empowering them with the ability to coordinate amongst themselves on a larger sensing task) will revolutionize information gathering and processing in many situations. Typical applications include habitat monitoring [5], tracking of moving objects [6] and environmental monitoring [7]. Other applications of Ad-hoc networks are target tracking, emergency rescue tasks and data acquisition in inhospitable or human inaccessible environments [8].

Multihop Ad-hoc networks have been the focus of recent research and development efforts in mobile networks [9]. MANET research generally assumes the following conditions [10]:

- Distributed operation. The control and routing operations are distributed among network devices.
- Multi-hop routing. Multi-hop forwarding decisions at each node require a distributed routing algorithm that can discover network topology so that routes can be formed between communicating nodes.
- Fluctuating link capacity. MANETs operate in the wireless domain. Atmospheric properties, competition from other sources of RF radiation and noise limit the capacity of a node to transmit information.
- Light-weight terminals. Since MANETs require mobility, nodes often run off battery power and conform to small form-factors that limit computing power.

1.2 Aim and Objectives

Routing protocols for mobile Ad-hoc networks are currently the subject of intensive research. The goal of routing is to deliver a packet from a source node to destination

node in a network. To solve the routing problem, nodes of the network execute a distributed “routing scheme”.

Geographic, or position-based routing uses the location information of nodes to find the route towards the destination. The co-ordinates of each node can be determined by using a GPS (Global Positioning System) receiver at each node and distributing this information to all other nodes within the network. Through location management schemes [11, 12], a source node is able to use this information to determine the location of the destination and identify all the intermediate nodes that could be used as a relay to the destination. Properties such as stateless nature and low maintenance overhead make geographic routing an attractive technique.

Conventional geographical routing protocols use location information as the only metric to select a relay node. Each node makes a decision about which neighbour to forward the message to based solely on the location of itself, its neighbouring nodes, and the destination node. The ideal FSPL (free space path loss) model is the basis of many protocols and is widely used in analytical and simulation studies. Each node has a fixed transmission range so that only the nodes within the range can receive the messages. Such a range can be modelled by a disk with fixed radius centred at the node. Hence, a maximum-distance greedy forwarding technique has been employed by those protocols in which a source node selects a relay node within its transmission range that is the closest to the destination in order to ensure a minimised hop count. However, the variability of wireless links exposes a key weakness in the greedy forwarding strategy which may result in packets being dropped and broken links. These schemes then have an innate weakness in terms of energy efficiency and link reliability.

The wireless nodes are normally energy and memory constrained devices, such as PDAs, cell phones, pagers and battery-powered sensors. Mobile users rely on a small battery to power the terminal, and a large part of the required power may be used in signal transmission. Even when using a laptop with a larger battery, the power requirements of the 802.11 specification form a significant factor in battery life [13]. The hardware constraints prevent the nodes from performing some of the energy costly operations that are utilised by the traditional wired networks. It is therefore desirable for a routing protocol to try and achieve the lowest possible transmitted power.

The reduction in transmitted power can have several benefits [14-17]. The battery life of a terminal may be extended, and frequency re-use can be greater due to the reduction in interference, so increasing capacity. Alternatively, the reduction in path loss may improve service. High data rates, or even any service, may be unavailable to users near the edge of a conventional cell due to the maximum transmitted power being unable to achieve the required signal to noise ratio. With relaying the only requirement is that users can achieve the required signal strength at the next relay, meaning that coverage and high data rates should be available to more users.

In order to provide robust performance in mobile Ad-hoc networks and hence cope with dynamic path loss conditions, it is apparent that research and development of energy efficient geographic routing protocols is of great importance. The aim of the work is to develop a novel geographic routing protocol which incorporates both the link quality and relay node location information to determine an energy efficient route from source to destination. The concepts of a gain region and a relay region have been proposed to define the area in where the candidate relay nodes will be selected, with the specific aim of maintaining a minimized hop count.

The research programme therefore comprises the following objectives:

- To study and investigate existing geographic routing protocols and the signalling processes.
- To study simulation models including network models, node models and process models of MANET routing protocols by using a leading discrete event driven modelling and simulation software, the OPNET Modeler [18].
- To model and simulate variable radio path loss model. The purpose being to adopt accurate models to generate realistic path loss conditions for MANET simulation and hence to obtain more realistic network performance.
- To develop an energy efficient geographic routing protocol incorporating variable path loss assignment. To analyse the signalling overhead required to operate the protocol compare its efficiency with that of established protocols for scenarios with different node density and network size.

- To seek to optimize the energy efficient geographic routing protocol by focusing on investigation of hop count with further improvement of relay region determination. The optimized energy efficient geographic routing protocol being designed to support a large number of hops to cope with longer separated source and destination nodes and provide improved performance in terms of both energy efficiency and optimised hop count.

1.3 Outline of the Thesis

In Chapter 2 wireless LAN technology and the IEEE 802.11 standard [19] are introduced. A range of routing protocols for mobile Ad-hoc networks are reviewed. Some key features of routing protocols for mobile Ad-hoc networks are discussed in particular for geographic routing.

In Chapter 3 a discrete-event simulation package, the OPNET Modeler, is introduced. The Modeler is considered as the simulation platform for developing, modelling and simulating the proposed routing protocols. Simulation models are developed and implemented on OPNET with a hierarchical structure. The network architecture for modelling of routing operation is determined. This is followed by a description of each of the simulation models used in OPNET.

Chapter 4 introduces the development of an energy efficient geographic routing protocol. The focus is made up of the path loss model of the wireless radio transmission. Attention is then drawn to energy efficiency as a key issue of geographic routing protocols. The development of geographic protocols is reviewed and discussed in order to determine how an energy efficient geographic routing protocol will be achieved. The concepts of gain region and relay region are described to exploit the novel feature of the proposed energy efficient geographic routing protocol in which candidate relay nodes are defined. For comparison several conventional forwarding strategies are discussed with the relative advantages and disadvantages. The proposed routing protocol is designed and implemented within OPNET to simulate the energy efficient operation based on the framework described in Chapter 3. The routing performance is analysed in terms of total transmission power and route lifetime to show the benefit of the energy efficient geographic routing protocol.

In Chapter 5 further improvement of proposed energy efficient geographic routing protocol is carried out to obtain improved routing performance in a scenario where the hop count is increased through modification of the relay region. Attention is drawn to the relationship between the hop count and the size of each relay region which determines the number of candidate nodes for each hop. Instead of using maximum-distance forwarding to achieve a minimised number of hops, the proposed protocol predetermines an optimal number of hops and uses this hop count for route determination. A size control mechanism for the relay region is proposed in order to maintain a reasonable size of the relay region for each hop. The simulated characteristics are also compared with the routing protocol presented in Chapter 5.

In Chapter 6 the signalling processes for the proposed routing protocols in Chapter 4 and 5 are introduced. With the enhanced signalling system, the routing protocol is able to obtain additional information to assist route determination. An investigation with a focus on the impact of different network densities and traffic patterns on the proposed routing protocol is also carried out. The signalling system is simulated and the amount of signalling information is determined and analysed, and compared with the signalling overhead of some established routing protocols.

Finally, Chapter 7 provides a summary of the research undertaken and the conclusions that have been drawn. The original contributions are also identified and suggestions for future work are presented.

Chapter 2 Mobile Wireless Networks

2.1 Introduction

Wireless LANs are used for providing network services in places where it may be very difficult or too expensive to lay cabling for a wired network. WLANs can be broadly classified into two types [20], infrastructure and Ad-hoc networks, based on the underlying architecture.

In infrastructure networks, a stationary node called an access point (AP) coordinates the communication taking place between nodes in the LAN. The APs can interact with wireless nodes as well as with the existing wired network. The other wireless nodes, also known as mobile stations, communicate via APs.

In Ad-hoc networks, no fixed infrastructure is needed. Mobile nodes communicate with each other. Signalling messages are forwarded through other nodes which are directly accessible.

The two main standards for WLANs are the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standard [21] and the European Telecommunications Standards Institute (ETSI) high-performance radio LAN (HIPERLAN) standard. The characteristics of mobile nodes modelled in this research project are based on the IEEE802.11b standard. The detail of the IEEE 802.11 standard is described in the following sections. Various routing protocols for Ad-hoc networks are also discussed in this chapter, especially for some routing protocols which are selected to compare the performance of the developed routing protocol.

2.2 The IEEE 802.11 standard

The IEEE 802.11 Working Group was formed in 1990 to define standard physical (PHY) and medium-access control (MAC) layers for WLANs in the publicly available ISM (the industrial, scientific and medical) bands. The objective of this standard is to provide wireless connectivity to wireless devices that require rapid deployment, which may be portable, or which may be mounted on moving vehicles within a local area. The IEEE 802.11 standard also aids the regulatory bodies in standardizing access to one or more radio frequency bands for the purpose of local area communication. The 802.11

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workgroup currently documents use in three distinct frequency ranges, 2.4 GHz, 3.6 GHz and 4.9/5.0 GHz bands. Each range is divided into a multitude of channels.

Currently, the most widely used are those defined by the 802.11b and 802.11g protocols which are introduced as follows.

2.2.1 IEEE 802.11b

The IEEE 802.11b standard [21] was ratified in 1999 with operations in the 2.4 GHz ISM band, which is freely available for use throughout the world. This standard is popularly referred to as Wi-Fi, standing for Wireless-Fidelity. It can offer data rates of up to 11 Mbps. As shown in Figure 2.1, there are 14 channels designated in the 2.4 GHz range spaced 5 MHz apart with the exception of a 12 MHz spacing before Channel 14. In Europe, the allowable channels are 1-13. Channel 14 is only valid for direct-sequence spread spectrum (DSSS) and Complementary Code Keying (CCK) modes in Japan.

As the IEEE 802.11b protocol requires 25 MHz of channel separation, adjacent channels overlap and will interfere with each other. There are three channels, channel 1, 6 and 11, available to use without overlap.

Figure 2.1 Wi-Fi channels in 2.4 GHz band [21]

A receiver has a minimum received power threshold which is called the receiver sensitivity that the signal must have to achieve a certain bitrate. If the signal power is lower the maximum achievable bitrate will be decreased or BER performance will decrease. The IEEE802.11b standard operates in the 2.4 GHz frequency range and uses the Direct Sequence Spread Spectrum (DSSS) modulation method. This results in a maximum data rate of 11 Mbps. As the distance between the access point and client increases, the data rate falls to 5.5, 2, and 1 Mbps, respectively. Table 2.1 shows the typical receiver sensitivity values for these data rates for a 802.11b device.

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Data Rate (Mbps)	Receiver Sensitivity (dBm)
11	-82
5.5	-87
2	-91
1	-94

Table 2.1. Typical Receiver Sensitivity VS Data-Rate of IEEE802.11b [21]

Usually, WLAN equipment has an output power of 15 dBm (about 30mW). The legal limit for radiated power (EIRP) for WLAN is generally set to 100mW (20dBm) in Europe. Figure 2.2 shows the indoor coverage of IEEE 802.11b under different data rates with 100mW at 2.4GHz. While the data rate decreases from 11Mbit/s to 1Mbit/s, the coverage of the AP increases from 48m to 124m in an indoor environment. This is because the receiver sensitivity increases as the data rate decreases.

Figure 2.2. The Coverage of IEEE 802.11b [22]

Table 2.2 below lists the transmission range for the IEEE 802.11b in the indoor and outdoor environment [22]. In the outdoor free space environment, the transmission range is 304m with 11Mbps. When the data rate is down to 1Mbps, the maximum transmission range reaches 610m. In multipath environments such as offices and other indoor environments, the maximum ranges at 1Mbps and 11Mbps are 124m and 48m respectively.

Data Rate (Mbps)	11	5.5	2	1
Indoor Range (m)	48	67	82	124
Outdoor Range (m)	304	-	-	610

Table 2.2. Transmission Range of IEEE 802.11b [22]

2.2.2 IEEE 802.11g

The IEEE 802.11g standard was published in 2003 [23]. This standard was involved in extending the 802.11b standard to support high-speed transmissions of up to 54 Mbps and uses the same Orthogonal Frequency-Division Multiplexing (OFDM) based transmission scheme as 802.11a, while maintaining backward compatibility with current 802.11b devices. The possible data rates for 802.11g devices using OFDM are 6, 9, 12, 18, 24, 36, 48, and 54 Mbps, and it also achieves 5.5 and 11 Mbps when using Complementary Code Keying (CCK), and 1 and 2 Mbps under Differential Binary Phase-Shift Keying (DBPSK) / Differential Quadrature Phase-Shift Keying (DQPSK) + Direct-sequence spread spectrum (DSSS) modulation schemes.

Table 2.3 lists the transmission ranges and modulation schemes for the IEEE 802.11g in the indoor and outdoor environment at different data rates [24]. Binary Phase-Shift Keying (BPSK), Quadrature Phase-Shift Keying (QPSK), 16 Quadrature amplitude modulation (16QAM) and 64QAM schemes are also used to support various data rates for IEEE 802.11g.

Data Rate (Mbps)	Transmission Type	Modulation Scheme	Outdoor Range (m)	Indoor Range (m)
54	OFDM	64 QAM	34	27
48	OFDM	64 QAM	61	29
36	OFDM	16 QAM	69	30
24	OFDM	16 QAM	99	43
18	OFDM	QPSK	122	55
12	OFDM	QPSK	145	64

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11	DSSS	CCK	149	67
9	OFDM	BPSK	168	76
6	OFDM	BPSK	198	91
5.5	DSSS	CCK	201	94
2	DSSS	DQPSK	210	107
1	DSSS	DBPSK	213	125

Table 2.3. Transmission Range and Modulation Schemes of IEEE 802.11g [24]

2.3 Routing Protocols in Mobile Ad-hoc Networks

A mobile Ad-hoc network (MANET) [25] is a self-organizing and self-configuring multi-hop wireless network, where the network structure may change dynamically. The changing topology of mobile Ad-hoc networks and the use of the wireless medium justify the need for different routing protocols compared to those developed for wired networks or centrally controlled cellular networks. Various routing protocols for mobile Ad-hoc networks have been proposed [26-34] to address the problem of decentralized routing.

In Ad-hoc networks, nodes do not start out familiar with the topology of their networks; instead, they have to discover it. The basic idea is that a new node may announce its presence and should listen for announcements broadcast by its neighbours. Each node learns about nodes nearby and how to reach them, and may announce that it, too, can reach them. A classification of Ad-hoc routing protocols is shown below in Figure 2.3 which differentiates the routing protocols according to their technique, link state, hop count and QoS in route discovery.

Figure 2.3. Classification of Ad-hoc Routing Protocols [35]

In Figure 2.3, Ad-hoc routing protocols are classified in three broad categories: flat routing, hierarchical routing and geographic position assisted routing. Flat routing protocols adopt a flat addressing scheme. Each node in the network participating in routing plays an equal role. Routing protocols in flat network structure fall into two categories, namely, table-driven proactive routing and on-demand reactive routing.

In contrast, in hierarchical routing, some nodes would be selected as header nodes amongst a cluster. Routing between nodes in different clusters must be directed via the header nodes. This scheme requires the complexity of selecting and maintaining the node hierarchy, but reduces the amount of signalling to support routing.

Routing with the assistance from geographic location information requires each node to be able to obtain location information through location services such as Global Positioning System (GPS).

2.3.1 Proactive Routing Protocols

Many proactive (table-driven) routing protocols stem from conventional link state routing protocols which are based on the periodic exchange of routing table information between all nodes in the network, even if no data traffic goes through. They aim to maintain fresh lists of all destinations and their routes. In this approach, each Ad-hoc node contains a routing table which specifies the next node in a route to any other node in the network. In mobile Ad-hoc networks, a route can be identified more quickly using proactive routing than reactive routing. However, the power and bandwidth consumption is larger due to topology table exchange among nodes. This takes place even if the network is in idle mode when no data transmissions occur in the network. So a large portion of the scarce wireless bandwidth is wasted on signalling overhead to broadcast routing tables. Structured routing can be utilized to reduce the route setup time and increase throughput. The main disadvantages of such algorithms are:

- Respective amount of data for maintenance
- Slow reaction on restructuring and failures

Some typical proactive routing protocols include the Fisheye State Routing (FSR) [36, 37], Fuzzy Sighted Link State routing (FSLS) [38], Optimized Link State Routing (OLSR) [28, 39, 40] and Topology Broadcast based on Reverse Path Forwarding

(TBRPF) routing protocol [29, 30]. In this thesis, OLSR is selected as one of the reference protocols to compare the performance with other routing protocols as well as my proposed protocol. More details of OLSR are described as follows.

2.3.1.1 Optimized Link State Routing (OLSR)

OLSR is an IP routing protocol which is optimized for mobile ad-hoc networks [28, 39, 40]. It is a table-driven proactive routing protocol based on link-states. Instead of relying on the number of hops to the destination node by distance vector protocols, link-state protocols determine the best route according to the link delay, load and bandwidth etc. It is acknowledged that link-state routes are more stable and accurate although estimating the best available route by this approach is more complicated than simply utilising hop count. Compared with pure link-state protocols, the control overhead information of OLSR is compact and the number of retransmissions required to flood these control messages is reduced.

The perfect network context for OLSR is a low mobile and dense network scenario. The control signalling overhead of OLSR does not require a reliable transmission link, which is very suitable for the dynamic condition in wireless networks. Mobility is supported in OLSR by periodically broadcasting the overhead control signals in the network. OLSR uses Hello and Topology Control (TC) messages to discover and then discriminate link state information throughout the mobile ad-hoc networks. Individual nodes use this topology information to compute next hop destinations for all nodes in the network using shortest hop forwarding paths. Topology information is exchanged with other nodes of the network regularly. Each node in the network selects a set from the next hop neighbour nodes as "multipoint relay" (MPR) nodes. The purpose of multipoint relay set is to reduce the overhead control messages and provide route optimization.

In OLSR, only nodes, selected as MPRs, are responsible for forwarding control traffic, intended for diffusion into the entire network. MPRs retransmit broadcast control messages while other one-hop neighbours receive messages and update their information accordingly but do not retransmit them [41]. MPRs provide an efficient mechanism for flooding control traffic by reducing the number of transmissions required. A comparison of LSR and OLSR protocols is shown in Figure 2.4 . Using

LSR 24 retransmissions are required to diffuse a message up to 3 hops, while OLSR requires only 11 retransmissions.

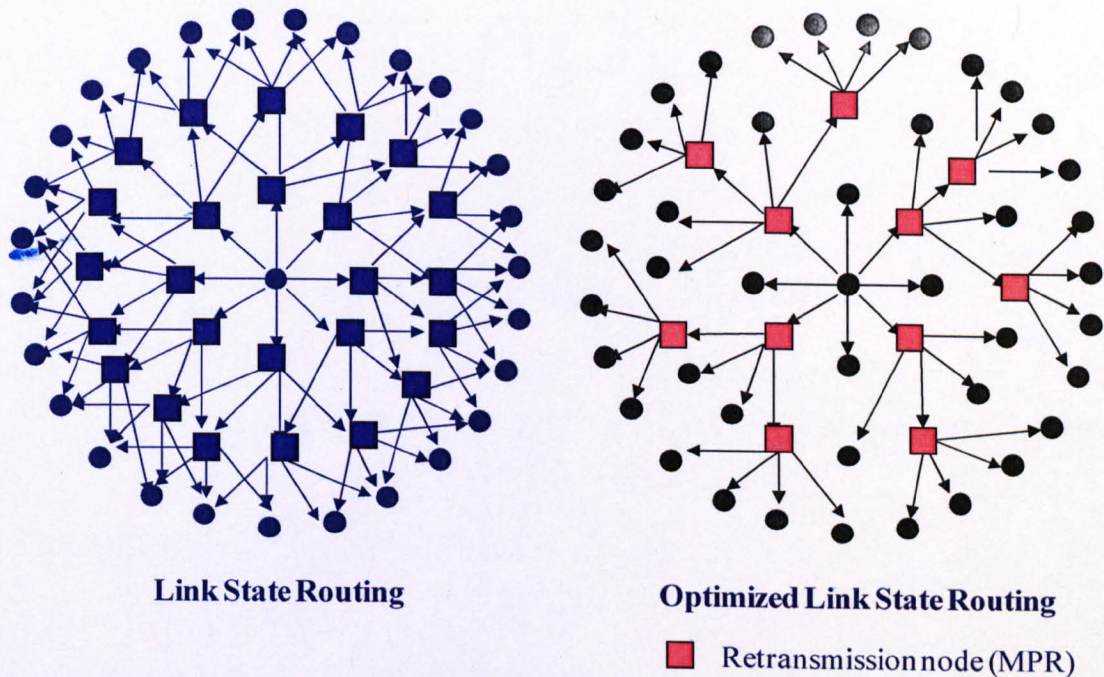


Figure 2.4. Comparison of LSR and OLSR

The route is established by using the routing table, which is based on the topology table and the neighbour node list saved in each node. The topology table is built by broadcasting Topology Control messages periodically which contain the multipoint relay set of each node. This makes the multipoint relay set for each node available to use for all other nodes in the network. The purpose of having a multipoint relay set in OLSR is to avoid sending the same overhead control message multiple times to the same node. This will optimize the energy and network bandwidth consumption. The Route discovery procedure is described as follows:

- Hello message is broadcasted by each node periodically that contains the information of its one-hop neighbours. The TTL of the Hello message is set to 1, which means the Hello message will not be forwarded further by its neighbours. Each node can obtain local topology information through the Hello message exchange.
- A node (selector) chooses a subset of its neighbour nodes based on the local topology information to act as its MPRs, which will be specified in the periodic Hello messages later. MPR nodes generally have two main roles:
 - When a packet is sent or forwarded by a node, all the neighbours of the

node will receive the packet. But only its MPR nodes will forward that packet.

- The MPR broadcasts its selector list periodically throughout the network with MPR flooding. Thus every node in the network learns which MPR nodes could reach every other node. The number of retransmissions of topology information broadcast and the size of broadcast packet can then be reduced. As the result, the bandwidth consumption of OLSR is much lower than the original link state routing protocols.
- With global topology information exchanged, stored and updated at every node, a shortest path from one node to other nodes through a series of MPRs could be computed using Dijkstra's algorithm [42].

The main advantages of OLSR are:

- Minimized latency
- Suitable for large and high density networks
- OLSR achieves more efficiency than classic link state algorithms in a dense network.
- OLSR can support QoS monitoring by providing link quality and bandwidth information in link state entries. Thus, the quality of the path is known prior to route setup.

Some disadvantages of OLSR include:

- The OLSR can reduce to a pure link state routing protocol in the situation of low density networks, every neighbour of a node becomes a multipoint relay.
- High signalling overhead of control messages (reduced by MPR usage)
- High computation of the route for each node
- Large storage requirement for routing information.
- Implementation complexity

2.3.2 Reactive Routing Protocols

The reactive protocols are based on on-demand route discoveries that update routing tables only for the destination that has traffic going to it. The protocols find a route on

demand by flooding the network with Route Request packets. Reactive routing protocols suffer from the initial route setup latency, introduced by their discovery phase. This degrades the performance of interactive and/or multimedia applications. With light traffic and low mobility network, on-demand reactive routing protocols scale well to large populations in terms of low bandwidth and storage overhead. However, when the traffic becomes heavy in a dense network, more sources will search for destinations. Also, in a high mobility scenario, the pre-discovered route may not be valid even after a short period, requiring repeated route discoveries on the way to the destination. Route caching then becomes ineffective.

The main disadvantages of such algorithms are:

- High latency time in route finding
- Excessive flooding can lead to network clogging

Examples of reactive routing include Ad-hoc On-Demand Distance Vector Routing protocol (AODV) [26] and Dynamic Source Routing protocol (DSR) [27], Associativity-Based Routing (ABR) [43], Lightweight Mobile Routing (LMR) [44] and Temporally-Ordered Routing Algorithms (TORA) [45]. Among the many proposed reactive routing protocols, AODV and DSR have been extensively evaluated in the MANET literature and are being considered by the MANET IETF Working Group as the leading candidates for standardization. The details of AODV and DSR are described in the following sections as aspects of their performance is compared with that of the routing protocol proposed in this thesis.

2.3.2.1 Ad-hoc On-Demand Distance Vector Routing (AODV)

Ad-hoc On-Demand Distance Vector Routing protocol (AODV) discovers routes on an “on-demand” basis via a similar route discovery process, but uses a different mechanism to maintain routing information. It is a “Hop-by-hop” protocol and uses routing table, one entry per destination. Intermediate nodes use routing table to determine the next hop based on the destination node. It relies on routing table entries to propagate a route reply control message (RREP) back to the source, and route data packets to the destination. In AODV, upon receiving a query, a node learns the path to the source, which is called backward learning, and enters the route in the forwarding routing table. The intended destination node receives the request and responds using the path traced by the query. A full duplex path can be established through this procedure.

To reduce the signalling overhead in a new path search, the query packet will be dropped during the flooding stage if it encounters a node which already has a route to the destination. After the path is established, it is maintained as long as the source node uses it. A link failure message will be reported to the source node recursively through the intermediate nodes if the path is invalid. This in turn will trigger a new query-response procedure to update the route.

A sequence number is used in AODV to ensure that routing information is up-to-date. The path discovery is established when a source node needs to communicate with a destination node, provided that the source has no routing information to the destination in its routing table. Path discovery is initiated by broadcasting a route request control message 'RREQ' that propagates in the forward path. If a neighbour node knows the route to the destination, it will reply with a RREP that propagates through the reverse path. Otherwise, the neighbour node will re-broadcast the RREQ. AODV maintains a path by using Hello messages, used to detect that neighbours nodes are still in range of connectivity. If a link is lost or broken, the node immediately engages a route maintenance scheme by initiating RREQs. The node can also learn about a lost link from its neighbours through route error control messages RERR [46].

2.3.2.2 Dynamic Source Routing (DSR)

The main difference between DSR and all other reactive protocols is that DSR is based on a source routing scheme in which the source node specifies the intermediate node sequence. In DSR, routes are stored in a route cache, data packets carry the source route in the packet header [27]. The entries which are stored in the route cache are updated as new routes are learned. When a node needs to send data to a destination node, it first searches its routing cache to see if it has a route to the destination. If a valid route exists in the routing cache, it will use that route to send the packet out. The source route is then carried by the data packet in the packet header. Route discovery is undertaken when a source needs a route to a destination. It is the major phase in DSR protocol, which is executed by flooding Route Request (RREQ) packets in the network as shown in Figure 2.5(a). The source node floods the network with RREQs. Each node receiving a RREQ adds itself to the path in the message and rebroadcasts it unless it is the destination node or it has the route to the destination in its cache. A destination node or a node knowing the route to the destination in its cache replies by unicasting with a RREP which contains the complete path built by intermediate nodes. RREQ and RREP

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routing process are programmable by developing the process models within the process editor. The behaviour of processes are specified using finite state machines (FSMs) and an extended high-level language called Proto-C. The FSMs are represented using state transition diagrams (STDs) as the state transition approach is well suited to discrete event systems. Proto-C is based on a combination of STDs, a library of functions known as kernel procedures, and the general facilities of the C or C++ programming language.

The description above essentially spans all the hierarchical levels of a simulation model on OPNET. Based on an object-oriented modelling approach and graphical editors, the layered modelling architecture and features of Proto-C language provide a flexible and open environment to support development of protocols and algorithms. As a powerful simulation package, OPNET Modeler incorporates a series of tools for model design, simulation, data collection, and data analysis. In this research use of OPNET for the development of the routing simulation models for MANET became an essential feature of the research programme.

Much effort was put into the design and development of the routing protocol model for MANET on OPNET: from top layer design of the routing protocol, establishment of the node structure and implement action of each functional block at the node level, to the development of process models based on Proto-C programming. Furthermore, in order to produce performance analysis statistics such as hop count, route power consumption, life-time of the link, etc., the desired statistics were planned and programmed while developing the process models.

3.2 Modelling of the MANET on OPNET

3.2.1 Network Model

The details of deploying a MANET model are introduced in appendix A. To establish a network model, various network parameters need to be configured such as network scale, node model type, number of nodes, distribution of the nodes etc. A typical example network for MANET on OPNET is shown in Figure 3.1. Each node within the network is uniquely identified by its IP address. IP auto-addressing is supported for MANET nodes. All MANET nodes are configured to belong to the same IP network. If there is a static assignment, that assignment will use a network address which is in the subnet to which all nodes must belong. If there is more than one static assignment and

the nodes have been given addresses in different networks, the first static assignment that is encountered becomes the network address of all the nodes in the subnet.

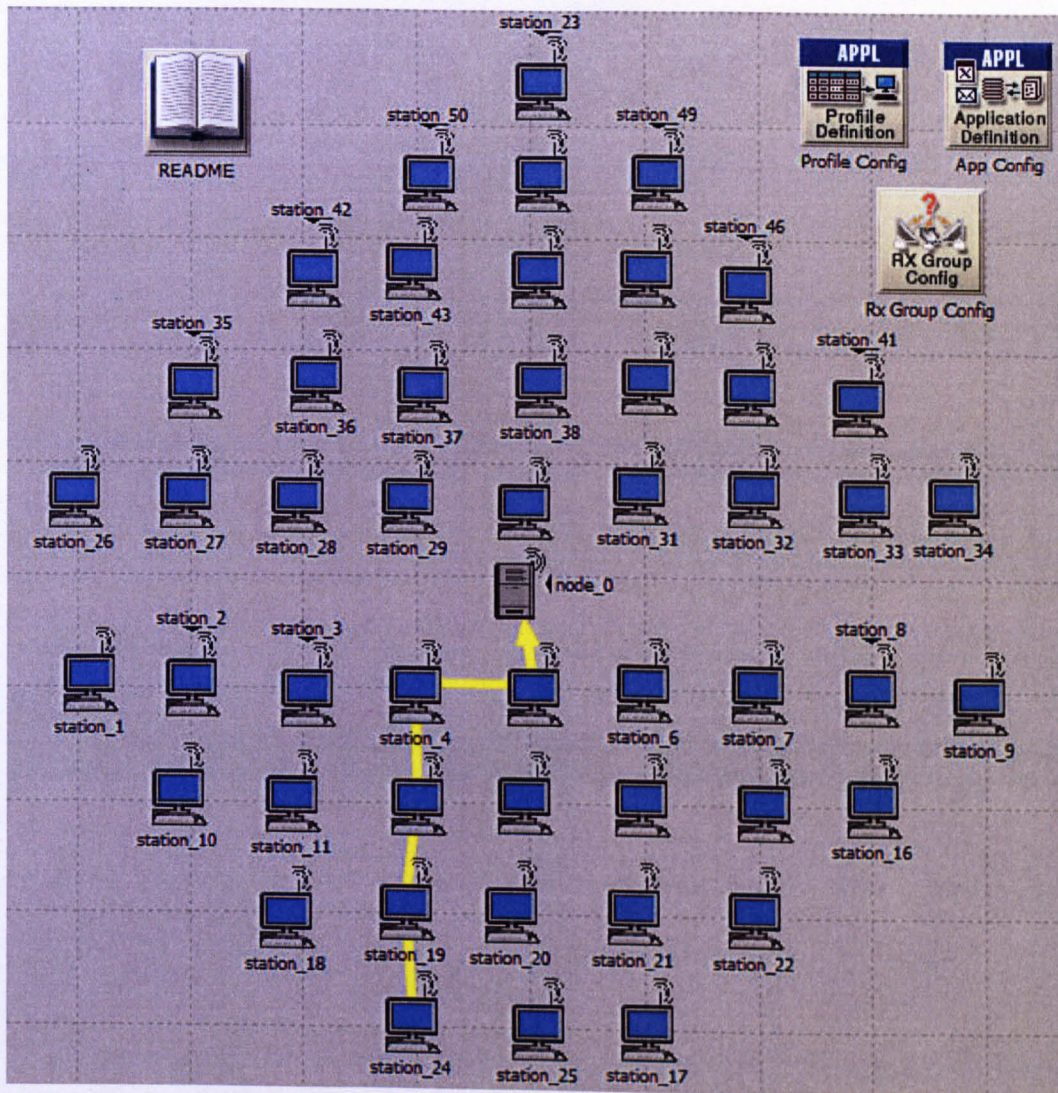


Figure 3.1 Network Example for MANET

Mobile node placement can be chosen from the three distribution functions which are random, grid and circular distribution. In this project, random distribution was used to simulate a realistic deployment of mobile nodes in the network. The maximum communication distance between two nodes is a function of three parameters: the transmission power of the sending node, the path-loss propagation model, and the reception power threshold (receiver sensitivity) of the receiving node. The Dynamic Receiver Group configuration object lets you compute receiver groups, which are the set of possible receivers with which a node can communicate within the maximum communication distance. This configuration object lets you specify:

- the criteria (channel match, distance threshold, and pathloss threshold) used to

determine which receivers belong to a receiver group

- when the groups are used
- how often group membership is computed

By restricting the set of possible receivers, you can reduce the number of transmissions sent out by the nodes in the network and reduce simulation runtimes. The decrease in simulation speed depends on the following factors:

- Number of possible neighbours for each node with respect to the total number of receivers
- Number of recomputations during the simulation (refresh interval)

3.2.2 Node Model

All MANET-capable nodes are included in the MANET object palette as shown in Figure 3.2.

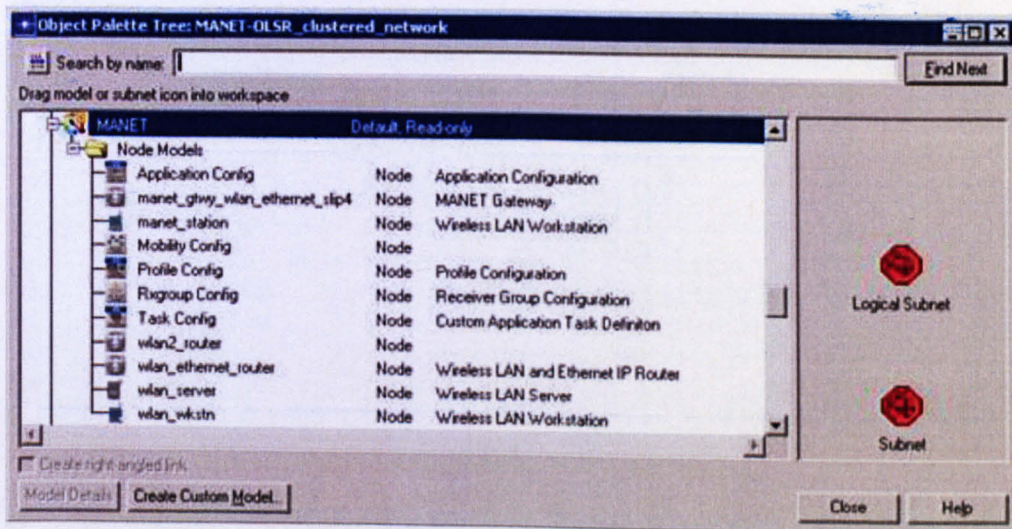


Figure 3.2 MANET Object Palette

The following nodes can be used in MANET network models.

- Wireless LAN workstations and servers: These node models are used to generate application traffic such as FTP, E-mail, and HTTP over TCP over IP over wireless LAN. These nodes can be configured to run any available MANET routing protocol.
- MANET stations: These node models are used to generate raw packets over IP over wireless LAN. They function as traffic sources or destinations and can be configured to run any available MANET routing protocol. For this node type, Layer-2 is wireless LAN.

- Wireless LAN routers and MANET gateway: These node models function as access points in a MANET. When MANET gateway functionality is enabled, these nodes can also connect MANET nodes to IP networks.

Routers within a MANET must have the same MANET routing protocol configured on every router interface under attributes IP > IP Routing Parameters > Interface Information > Routing Protocols on a MANET station, as shown in Figure 3.3 below.

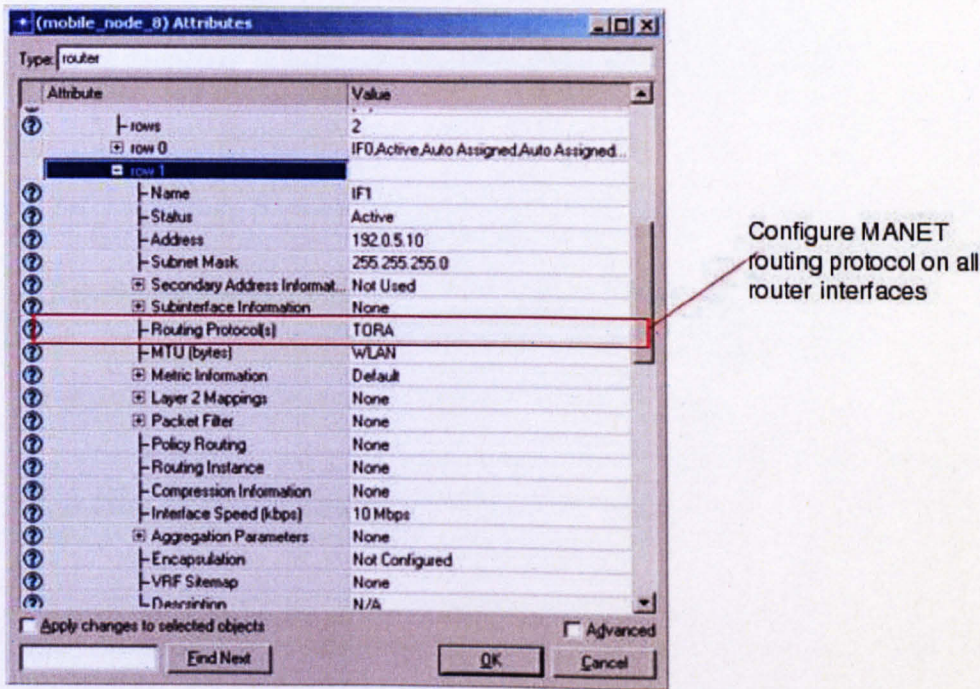


Figure 3.3 MANET Routing Configuration on Interface

Applications are the predominant sources of traffic in the network. It is the traffic generated by applications that loads the network, makes demands on the bandwidth and the underlying network technology, and creates signalling overhead in MANET. The standard applications, such as FTP and Email, can be configured by the “Application Config” utility node to generate simulated traffic in the network model. To be an accurate representation of the application, an application model should have the same traffic characteristics in terms of the size of the packets generated, the rate at which they are generated etc. Raw packet generation can also be used by MANET stations in the network model. Raw packet generation can be configured from "MANET Traffic Generation Parameters" attributes on a MANET station in the Project Editor as shown in the following Figure 3.4.

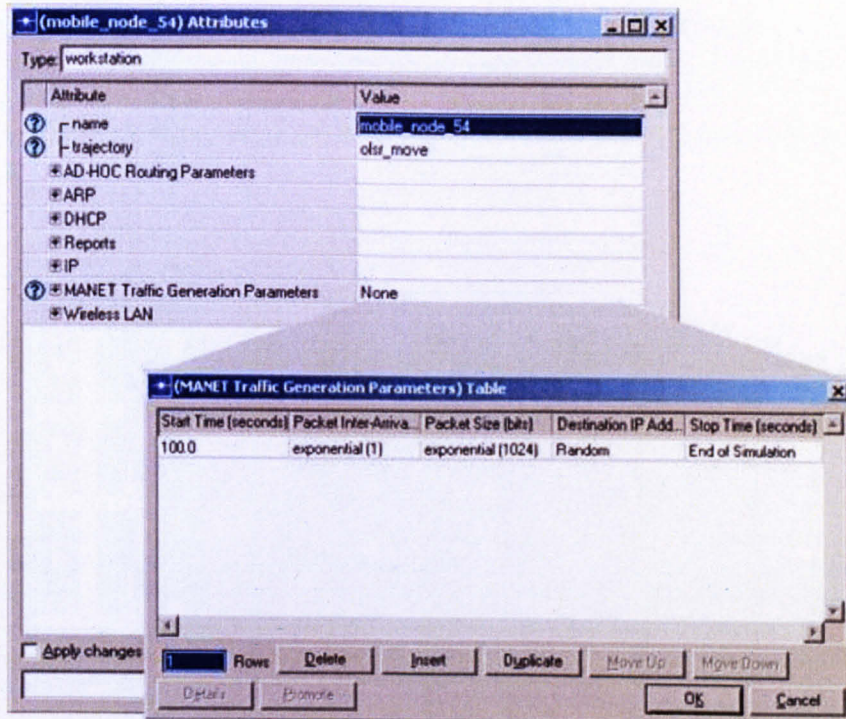


Figure 3.4 Packet Generation Parameters

The MANET traffic generator enables superposition of numerous packets' generators, which are defined by the following parameters:

- Start time of generator activity (s)
- Statistical distribution of time between packets (s)
- Statistical distribution of the packet size (bits)
- IP address of final destination
- End time of generator activity (s)

MANET Traffic Generation Parameters	(...)
Number of Rows	1
100.0	
Start Time (seconds)	100.0
Packet Inter-Arrival Time (seconds)	uniform (2.0, 2.5)
Packet Size (bits)	constant (1024)
Destination IP Address	Random
Stop Time (seconds)	End of Simulation

Figure 3.5. MANET Traffic Generation Parameters

Figure 3.5 shows a sample of the MANET traffic generation editor. Number of Rows defines the number of different traffic patterns in the simulation. A uniform distribution is used in the simulation to generate random values for packet inter-arrival times. This parameter determines when packets are generated in the source node for transmitting to the destination node. In probability theory and statistics, the uniform distribution,

sometimes also known as the rectangular distribution, is a distribution in which all intervals of the same length (in this case 10^{-6} s) have equal probability within the defined min and max range as shown in Fig 3.6 in which $P(x)$ is the probability density function.

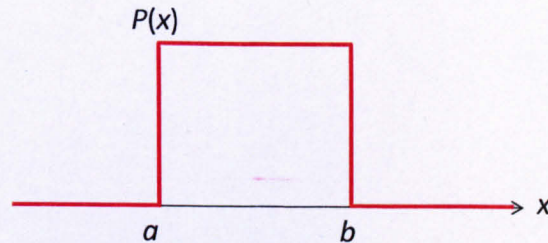


Figure 3.6. The probability density function of Uniform Distribution

The maximum transmission range between two MANET nodes is a function of three parameters: the transmission power of the sending node, the path-loss propagation model, and the reception power threshold (receiver sensitivity) of the receiving node. Based on the configured values of these parameters, you can model MANET networks in which the communication distance is more than 300 meters. The IEEE 802.11 standard limits the distance between nodes to 300 meters. Therefore, a network that extends beyond 300 meters might incur a performance degradation in the WLAN MAC algorithm.

The receiver sensitivity concept is implemented through the reception power threshold attribute with MANET models. Packets with a reception power that is lower than the threshold cannot make the receiver lock onto their signal and will be treated as noise packets. When the signal of these packets is very weak, the receiver can simultaneously receive another packet with a strong signal from a nearby neighbour.

The transmitter power can be configured on each MANET node. Transmission range is configured in the Transmit Power attribute as shown below.

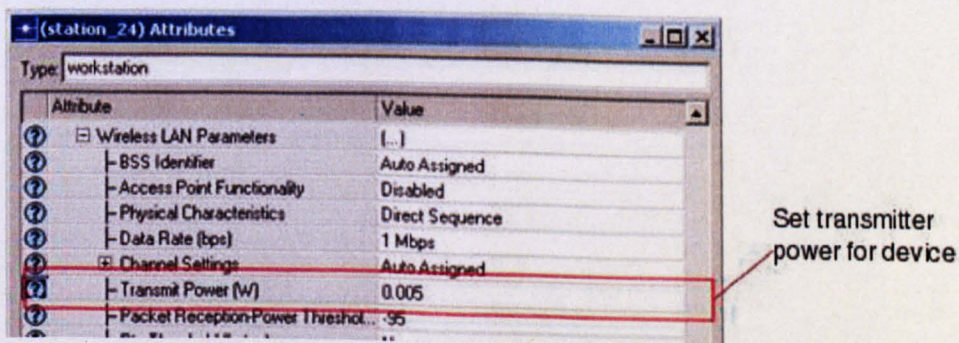


Figure 3.7 Transmit Power Attribute

As shown in Figure 3.8, the node model of MANET simulates the protocol stack. GRP, DSR, AODV and TORA protocols are implemented over IP while OLSR is implemented over UDP.

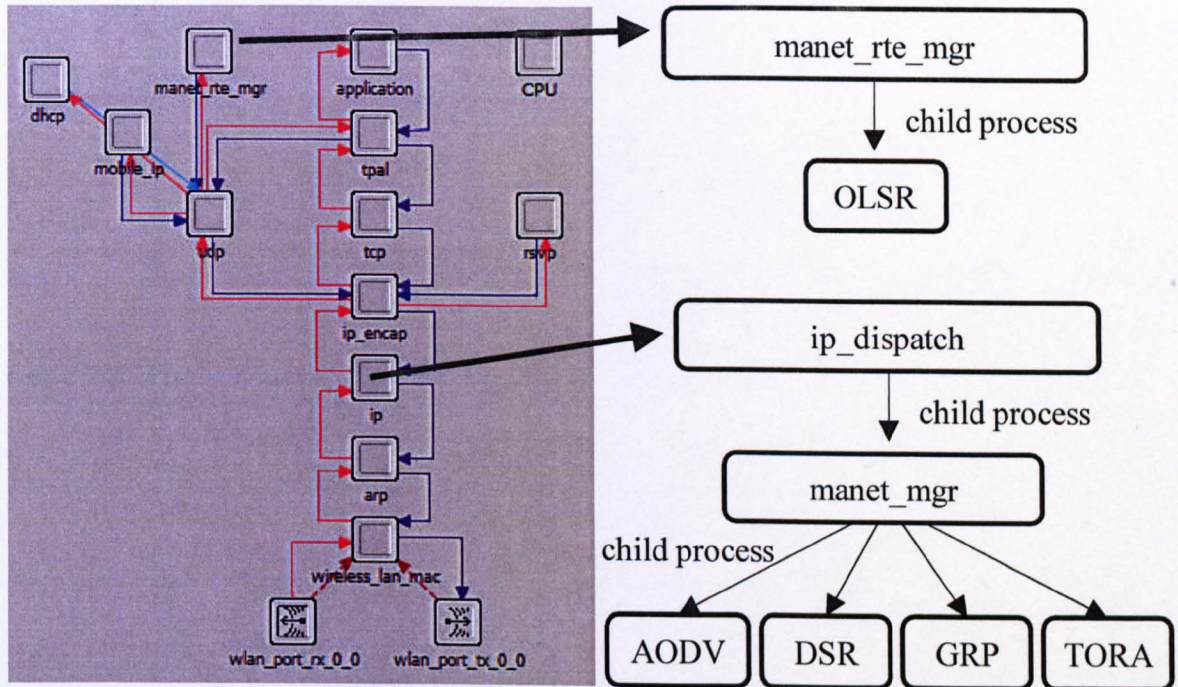


Figure 3.8 MANET Node Model Architecture

Geographic Routing Protocol (GRP) is implemented at the IP layer. As shown in the figure above, `ip_dispatch` is the root process for IP and has as a child process, `manet_mgr`. `manet_mgr` and `manet_rte_mgr` are the manager process models which provide a common interface to multiple MANET routing protocols. `manet_mgr` is responsible for spawning the GRP child process when a node is configured for GRP.

Figure 3.9 shows the flow chart of signalling packets from routing protocols. The signalling messages generated by MANET routing protocols are sent to the `manet_mgr` process model and then to `ip_dispatch` and the IP routing process and finally to the MAC/physical layer for transmission.

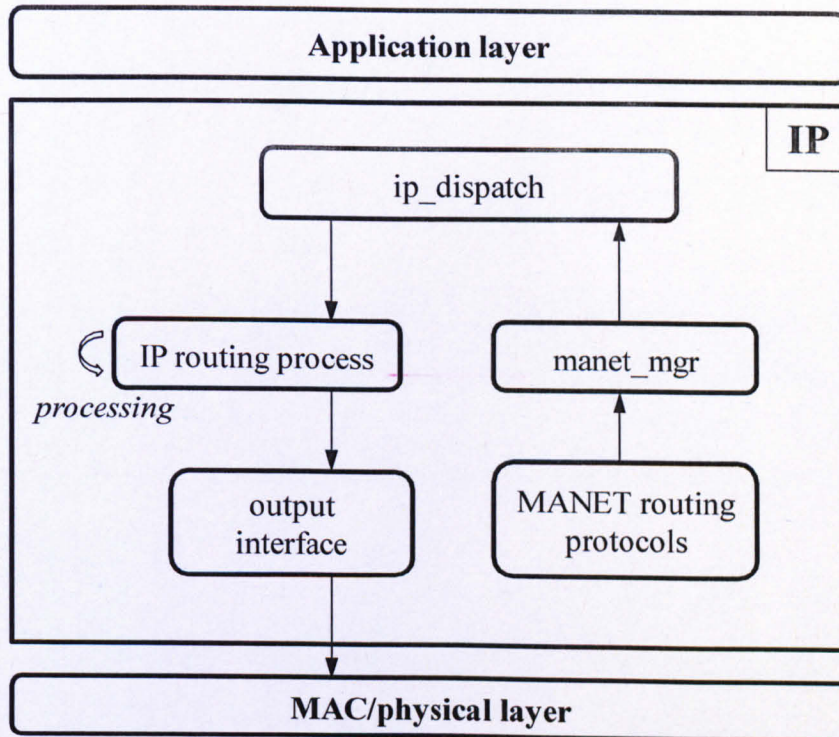


Figure 3.9 Signalling Packet from Routing Protocols

3.2.3 Process Model

The `grp_rte` process as shown in Figure 3.10 implements the GRP routing algorithm as well as the improved GRP protocol which is proposed in later chapters.

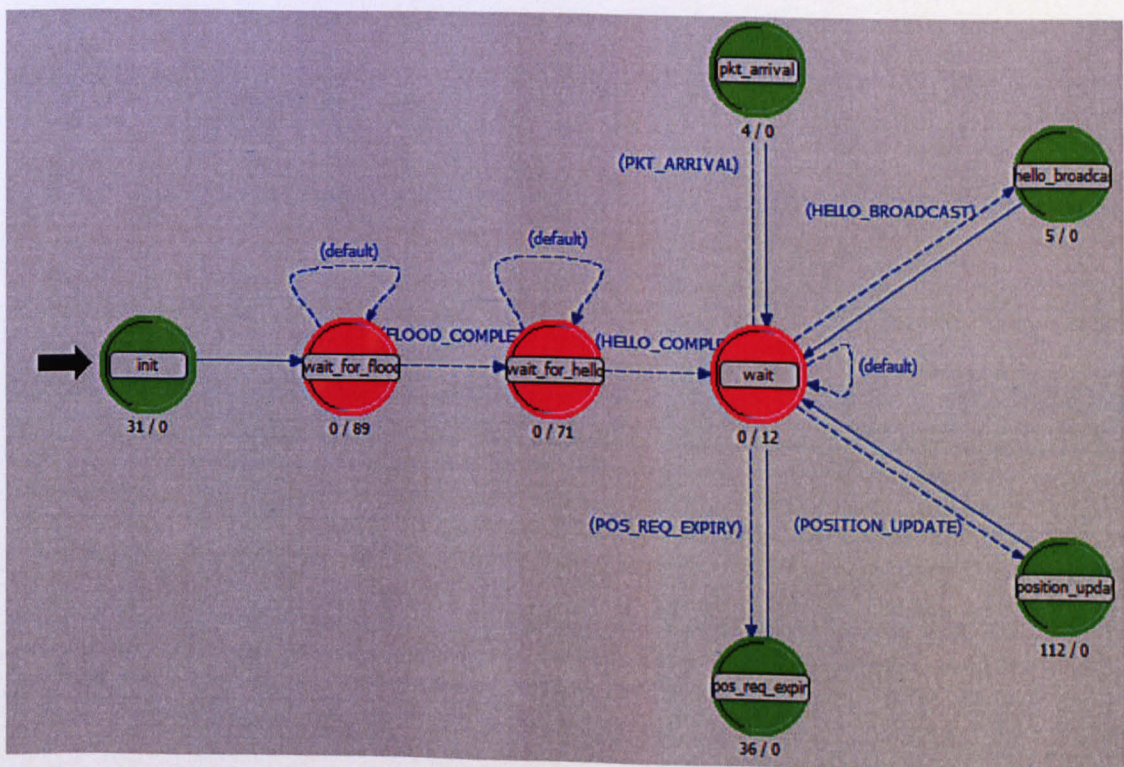


Figure 3.10 `grp_rte` Process Model

Init state: This state consists of the initialization of the process model. User defined attributes are loaded and routing information tables are initialized. A self interrupt is scheduled to move to the next state. A jitter between 0 and 5 seconds is added before sending out flooding packets. Once the initialization step is accomplished, the process transits to the *wait_for_flood* state.

wait_for_flood state: This state performs initial flooding so that it bootstraps to reach steady state. A flooding message is broadcast to all nodes in the network to inform its presence and location information. A self interrupt is scheduled to move to the next state to initiate the first Hello Interval. A jitter between 0 and 5 seconds is also added before sending out hello packets.

wait_for_hello state: This state is the initialization of the hello process. A node broadcasts a Hello message in order to advertise its presence to the neighbourhood. A schedule is made for the next periodic hello process according to a pre-defined hello interval. Once this step is accomplished, the process transits to the *wait* state.

wait state: This is the idle state for the node. It will move to other states when a new event is triggered such as the arrival of packet etc.

pkt_arrival state: When a packet arrives, the node checks its attribute and handles the packet appropriately based on its type. The flow chart for this state can be seen in the Figure 3.11 below.

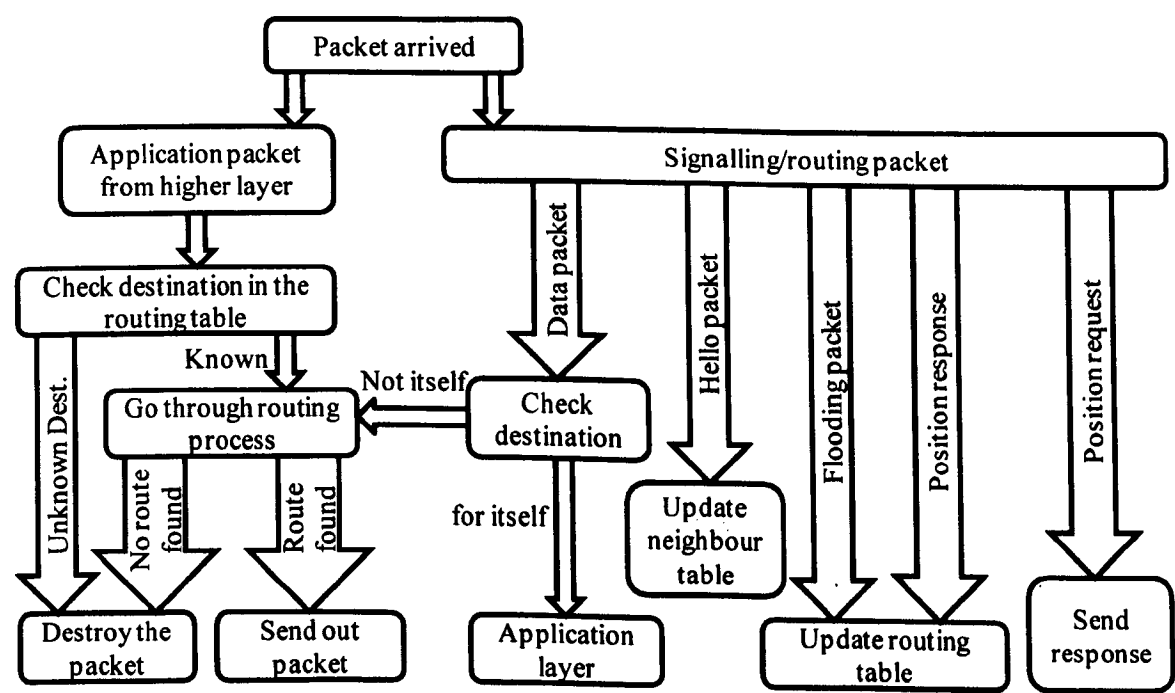


Figure 3.11 Flow Chart for *pkt_arrival* State

The arrived packet can either be:

- A higher layer application packet waiting to be transmitted when a route is found.
- A MANET signalling/routing packet.

If the packet is from the application (higher) layer, the node then checks if the destination exists in its routing table. The application packet will be destroyed if the destination is not known to this node. Or the node will go through the routing process to find a relay node to send the packet to if the destination exists in the routing table. However, the packet will be destroyed if no next hop can be found.

If the arrived packet is either a GRP control packet or a data packet from the lower layer then if the packet was sent out by the node itself, it will be discarded, if not, the node will check the type of option set in the packet. The packet may be one of the types listed below:

- A Hello message. The node will add or update the neighbour node information to the neighbour table.
- A flooding message. The routing table of the node will be updated with the information provided by the message.
- A data packet. The node will check the address of the destination node. If the packet is for this node, it will be sent to the application layer. Or this node is just an intermediate node to the destination, the routing procedure will be executed to find the next relay node for the packet.
- A position request option. The node will check if the request is for itself or one of the nodes within its routing table. If so, a position response packet will be sent back otherwise the packet will be resent out to the neighbourhood.
- A position response option. The node will update the routing table with the information contained in this message.

hello_broadcast state: This state broadcasts a hello request message and schedules the next periodic hello.

position_update state: Check if the node has moved greater than the pre-defined threshold distance which the node needs to flood its current position to all other nodes in the network.

pos_req_expiry state: Find the list of destinations that the node is still waiting on the position information. When the position request timer has expired, node resends the position request message to the neighbour node and schedules the position request timer for receiving a position response message.

The general information about process model for AODV, DSR and OLSR can be found from OPNET website and the user manual [60, 61].

3.2.4 Medium Access Control Model in OPNET

OPNET supports simulation of Ad-hoc wireless networks using the physical layer and medium access control layer models. The IEEE 802.11 MAC protocol with Distributed Coordination Function (DCF) [21] is deployed as the MAC layer in the simulations. DCF is the basic access method used by mobiles to share the wireless channel and avoid hidden and exposed terminator problems [56]. The access scheme is Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) with acknowledgements. The nodes can make use of Request To Send / Clear To Send (RTS / CTS) channel reservation control frames for unicast, virtual carrier sense, and fragmentation of packets larger than a given threshold. In the model, the RTS/CTS mechanism is deployed to minimize the effect of collisions over the wireless medium.

3.3 Model development on OPNET

3.3.1 Modelling wireless effects on OPNET

MANETs have been proposed for scenarios with complex obstacle-rich environments. Therefore, it is important that MANET protocols be carefully evaluated in such conditions. Factors affecting received power include wavelength, distance, terrain, humidity, temperature, objects in the path etc. Wireless links are typically less reliable than wired links and need to be characterized appropriately.

‘Pipeline’ is used in OPNET to simulate and denote a sequence of calculations for the transceiver characteristics such as path loss, signal strength and bit errors etc. The details of radio pipeline stages are described in appendix B. Each stage performs a different calculation for a radio transceiver.

The fundamental performance measure computed by the default Radio Transceiver Pipeline is the average power level of signals received by radio receiver channels. By

computing this value for every relevant signal arriving at each radio receiver channel, the Received Power Model, which is the seventh stage of the pipeline, enables later stages to compute signal-to-noise ratio (SNR) and then derive bit error rate (BER).

The computation of received power occurs independently for each packet that is able to reach and affect the radio receiver channel. The result of the Received Power Model invocation for each packet is a single double precision floating point value which represents the received power level for the packet.

For all arriving packets, whether valid or invalid, the average power level of the received signal is computed. This computation is a link budget which takes into account the initial transmitted power, the path loss, and receiver and transmitter antenna gains. The power (in units of watts) allocated to the transmission is obtained from the packet's transmission data attribute. The base frequency of transmission and the bandwidth of transmission are also obtained from the transmission data attributes. The values of these two variables are then used to compute the centre frequency of the transmission. The wavelength λ , of the packet transmission is given by the propagation velocity of light, c , divided by the centre frequency.

The propagation distance (in meters) for the packet transmission is obtained from the packet's transmission data attribute. The free space propagation loss is computed as a function of wavelength and propagation distance with the relation given in the equation below.

$$P_d = \left(\frac{\lambda}{4\pi D} \right)^2 \quad (3.1)$$

Where P_d is the path loss, D is the distance between transceivers, λ is the frequency.

A link model is developed on OPNET to simulate the random path loss between nodes to facilitate the analysis of routing performance for MANET. This work will involve a matrix G for the extra path loss in addition to the FSPL model. Assume that N nodes exist in a network numbered from 1 to N . A matrix G for extra path loss can be defined as follows.

$$G = \begin{pmatrix} G_{11} & G_{12} & \dots & G_{1N} \\ G_{21} & G_{22} & \dots & G_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ G_{N1} & G_{N2} & \dots & G_{NN} \end{pmatrix} \quad (3.2)$$

G_{ij} is the extra path loss between node i and j . The range of G is between 0 and 20 dB. The overall path loss is then calculated in the following equation.

$$P_{ij} = P_d + G_{ij} \quad (3.3)$$

Depending on the path loss between node i and j , a transmission on this link is either possible or not which defines 1 or 0 for C_{ij} . A connectivity matrix C with N nodes is expressed as:

$$C = \begin{pmatrix} C_{11} & C_{12} & \dots & C_{1N} \\ C_{21} & C_{22} & \dots & C_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ C_{N1} & C_{N2} & \dots & C_{NN} \end{pmatrix} \quad (3.4)$$

With this connectivity matrix, the connection status between any nodes can be obtained while conventional method only uses distance metric to determine nodes connectivity.

3.4 Summary

In this chapter, OPNET modeller has been introduced and MANET models have been discussed. The simulation carried out in this project follows the characteristics discussed in this chapter.

CHAPTER 4 Development of an Energy Efficient Geographic Routing Protocol (EE-GRP)

4.1 Introduction

Geographical approaches build on the proactive or reactive techniques previously described and in addition incorporate geographical information to aid in routing [11, 57-61]. This geographical information can be in the form of actual geographic coordinates as obtained through the global positioning system (GPS), or can be obtained through reference points on some fixed coordinate system. The use of geolocation information can prevent network-wide searches for destinations, as either control packets or data packets can be sent in the general direction of the destination rather than in all directions if the recent geographical coordinates for that destination are known. This reduces the control overhead generated in the network; however, all nodes must have continual access to the geographical coordinates of network nodes for these approaches to be useful.

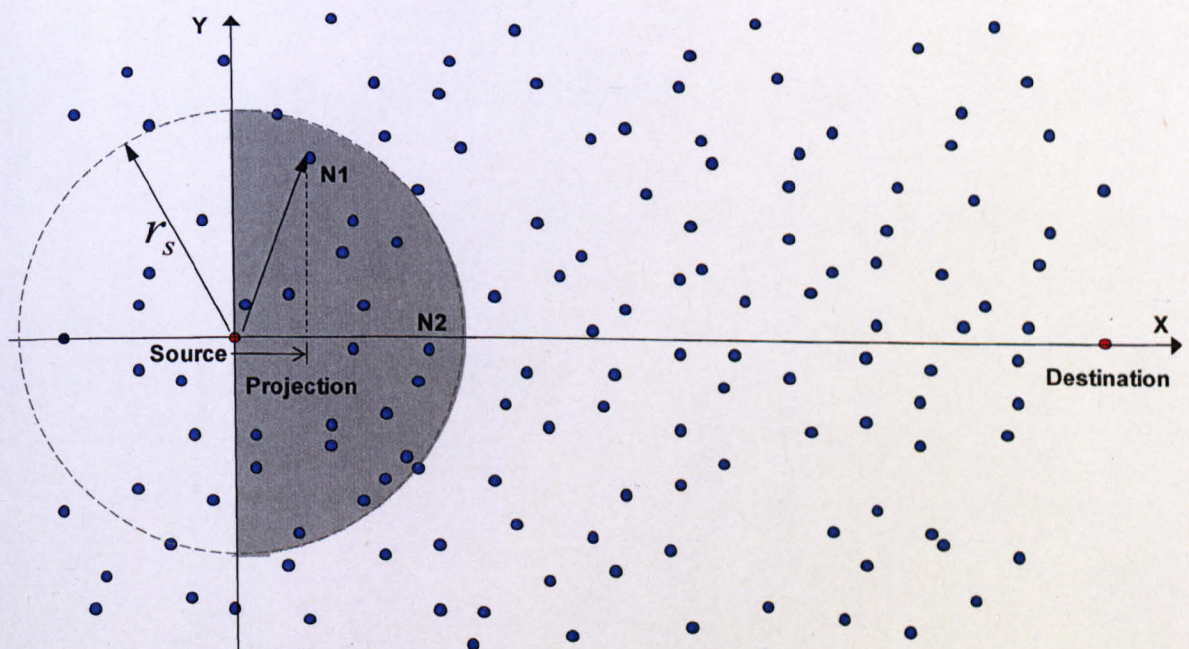


Figure 4.1. Forwarding Progress for Geographic Routing

Most geographic routing approaches are based on the concept of progress, which is defined as the projection of the distance travelled from the source node to any

neighbouring nodes in a forward direction along the line from the source to the destination as shown in Figure 4.1. Any neighbouring nodes, (as previously described), of the source normally fall within the maximum transmission range r_s . Any nodes within the shaded area identified in Figure 4.1 are those with positive progress toward the destination. Candidate nodes for use in relaying data, are therefore those neighbour nodes which have a forward progress less than r_s and lie within the shaded area shown in Figure 4.1.

A typical example of forward strategy for geographic routing is the maximum-distance greedy forwarding routing scheme in which packets are forwarded to a neighbour which is closest to the destination D and lies within the maximum transmission range. In the example shown in Figure 4.1 this protocol would choose node N2 as the relay node. The maximum-distance greedy forwarding scheme is designed with the following aims:

- Maximum Forwarding Distance
- Minimum hop count
- Minimising network messaging
- Reducing power consumption

Some basic position-based routing algorithms have also been proposed which are discussed below.

Consider the angle formed by line segments SN and SD, where S is the forwarding node, N is a potential next hop and D is the destination. The compass routing algorithm [62], forwards packets to the neighbour N that forms the smallest angle with the destination. Compass routing algorithm is also memoryless.

Randomized Compass routing algorithm [63] is a variation of the compass algorithm that avoids loops with random decisions. It is also a memoryless algorithm. Consider as in the compass routing the line defined by forwarding node and destination. At each node, two options are considered to route a packet: the neighbour with smallest angle above that line and the neighbour with smallest angle below that line. One of those neighbours is randomly chosen to be the next hop.

Consider that line SD is the x-axis, where S is the forwarding node and D is the destination node. In the Most Forwarding within Radius [62] (MFR) protocol node S forwards the packet to the node A that maximizes progress along x-axis.

Geographical Distance Routing (GEDIR) [64] resembles the greedy algorithm, with a subtle difference. Packets are sent to the neighbour node that is closest to destination D, despite the distance of the source node to the destination. This means that a packet can be sent to some node that is actually more distant from D than the sending node S. The rationale for this is that node may have some neighbour which is closer to D than S is. The only kind of loop that may occur in this algorithm is between two consecutive nodes and, therefore, one can make it loop-free.

Many other forwarding schemes have been studied and proposed [7-14]. Examples of nodes chosen using such schemes are shown in Figure 4.2. In all these schemes the location of the final destination (D) is assumed to be known by the source node. The *Most Forward within Radius* (MFR) routing scheme [65] selects M1 as the chosen relay node as it provides the greatest forwarding progress toward the destination, D, within a defined maximum radius r_s . MFR is a progress-based algorithm competitive in terms of hop count, i.e. designed to offer the lowest number of hops to the destination which also provide minimised end-to-end delay. However, as indicated in [66-69], long distance links are unreliable in reality due to the unpredictability and rapid change of wireless conditions which significantly affect the link quality. Hence the long-hop-distance route selected by MFR may not be viable and may fail.

Compass Routing [62], selects node M2 which is closest to the straight line between source and destination, the source node uses the location information of the destination D to calculate its direction. Then the packet is forwarded to the neighbour M2, such that a node closest to the direct SD path is chosen. This process repeats until the destination is eventually reached. The route selected by *Compass Routing* gives the minimised overall distance but may need more hops than MFR.

M3 is selected by the *Nearest with Forward Progress* (NFP) routing [70] scheme as it is the closest node to the source node S while still offering forward progress. The principal aim of this scheme is to minimise the power consumption for each single hop, however it can lead to a large hop count. NFP is not suitable for high density networks because

the delay caused by the large number of hop count for the route may exceed system requirements.

M4 is the node choice for *greedy forwarding based* routing [71] which chooses the closest node to the destination, although M4 has less forward progress than M1 which is selected by MFR. All these protocols use position information as the only metric for route decision and ignore link quality. To resolve this problem, an energy-aware geographic routing protocol needs to be specified to choose a relay route which offers low power consumption through use of a relay node with good quality links while also providing adequate progress toward the destination.

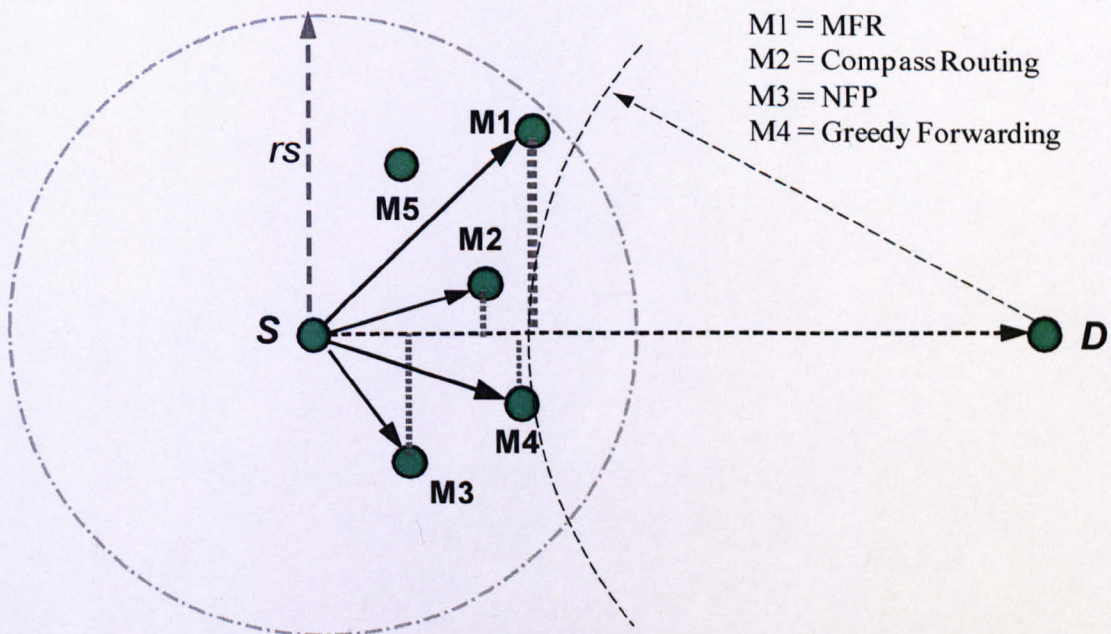


Figure 4.2. Examples of Node Choice for Different Geographic Routing Protocols

4.2 Energy Efficient Forwarding for Geographic Routing

Many energy based routing protocols have been proposed [72-78] for mobile Ad-hoc networks. An energy-aware geographic routing protocol which aims to reduce the total energy consumption will not only focus on distance-based greedy forwarding, but also the power requirement for selected links which then becomes one of the major metrics for geographic route determination.

The total power consumption of a selected route can be expressed as the sum of powers required for each individual hop as in the Equation 4.1.

$$P_{Total}(d) = \sum_{x=1}^n P_{rx} \quad (4.1)$$

Where P_{Total} is the total power consumption of the route, P_{rx} is the required transmission power for each hop of the selected route which does not include the processing power and n is the number of hops.

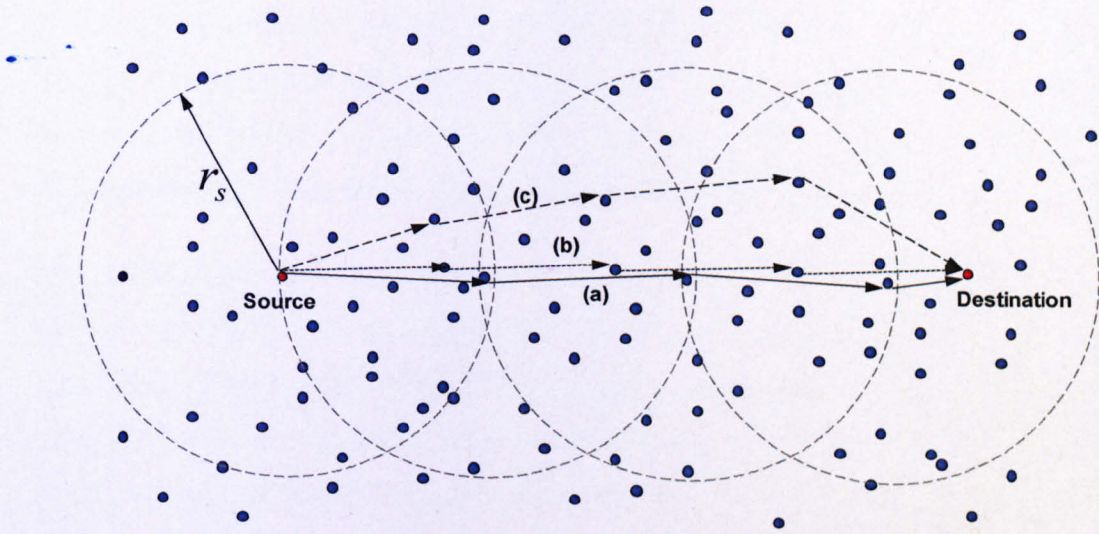


Figure 4.3. Forwarding Schemes Comparison with Four Hops

- (a) Maximum-Distance Forwarding
- (b) Optimal-Distance Forwarding
- (c) Energy-Greedy Forwarding

Examples of routing protocols which seek to reduce energy consumption are shown in Figure 4.3. In this figure, route (a) shows an example of the maximum-distance forwarding scheme for a simple network in which the source and destination are separated by distance d and which assumes a FSPL model for all inter-node hops. The source node finds a relay node closest to the destination within its maximum transmission range r_s until the final relay node falls within r_s of the destination. This process provides a minimum hop count, which helps to minimise total energy consumption.

An improved optimal-distance forwarding (ODF) scheme which is also based on a FSPL model is shown in (b). In this case, instead of forwarding the packets to the neighbour closest to the destination or the neighbour which has the maximum forward

progress as in (a), the packets are transmitted to the neighbour which is closest to the energy optimal relay position which can be shown is that for which each hop has an equal distance which in the four hop case shown, is $d/4$ [78, 79].

Neither of the above schemes takes into account the fact that the actual path loss between nodes is rarely that given by the FSPL model and will actually vary with both node location and time. The effect on the chosen source-destination route of considering variable inter node path loss is shown in route (c) which uses an energy-greedy forwarding scheme with a realistic path loss model. In this case a relay node is selected not only by its location but also by its link quality i.e. the path loss to it, and the total energy consumption of the route is then minimised by selecting the node which has the lowest energy consumption for each hop. This may lead to a longer source-destination path than the above algorithms, but would provide a lower total energy consumption.

If a realistic path loss model is used, the maximum-distance forwarding route (a) may not provide viable links because potentially the path loss to the chosen nodes may be very high. Also the energy optimal relay position (b) may not provide optimized energy consumption for a route because the actual required transit power is determined not only by the distance of the link, but also by the arbitrary path loss which is not identical for each hop. In order to develop an energy efficient geographic routing protocol, the principle of the power requirement between nodes will be studied and analysed.

Note the circles shown in the above figure reflect the maximum transmission distance for the nodes used in route (a). More circles should be drawn around the relay nodes for the other schemes, but are omitted to aid clarity.

4.3 The Concept of a Gain Region

4.3.1 Geometrically Based Analysis for Transmission Power Reduction

The main criteria influencing the protocol design proposed in this work is energy efficiency, that is the protocol seeks to reduce total power consumption by analysing how energy can be reduced between the source and the destination and defining areas for relay node selection rather than simply using a straight line distance based forwarding scheme. Introducing a model which seeks to minimise power consumption is aided by definition of a new concept called gain region between source and

destination. When nodes lying within this region are chosen for relay purposes it can be shown that the total power consumption of a multi-hop route can be lower than the required power for the direct transmission between source and destination. This is shown below by reference to Figure 4.4, for a simple 2-hop route.

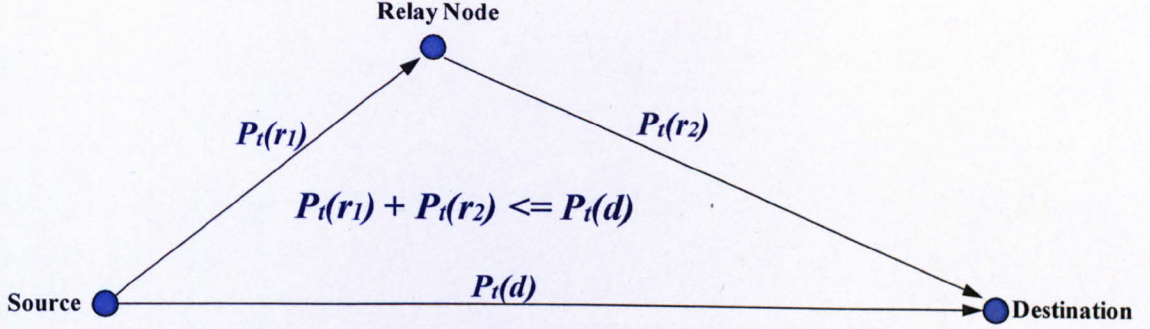


Figure 4.4. Two-Hop Example

In Figure 4.4, $P_t(d)$ is the required transmission power for a direct link from source to destination node. $P_t(r_1)$ and $P_t(r_2)$ are the transmission powers for the source and relay node in a 2-hop route respectively. The total power consumption for a two-hop route through a relay node may be lower than that of the direct transmission between source and destination i.e.

$$P_t(r_1) + P_t(r_2) \leq P_t(d) \quad (4.2)$$

If certain conditions are satisfied. To determine those conditions consider a path loss model in which the received signal power at distance x from the transmitter can be calculated by:

$$P_r(x) = \frac{P_t G_t G_r}{L} \left(\frac{\lambda}{4\pi x} \right)^\eta \quad (4.3)$$

where P_t is the transmitted signal power, G_t and G_r are the antenna gains of the transmitter and the receiver respectively these gains are assumed to be the same for all nodes in the network, λ is the wavelength, and L is the system loss which are also assumed to be constant for all nodes. The path loss exponent η is environmentally dependent, and is typically in the range of 2 to 5 where 2 is for propagation in free space and the larger values for the path loss in environments such as buildings, stadiums and other indoor environments.

For the definition of a gain region, we assume a power control mechanism is incorporated within each node. This mechanism adapts the transmitted power to the link loss so that the received power at each mobile node P_r is constant. P_t is therefore proportional to some power η of the distance between two nodes x . Equation 4.2 then becomes:

$$\frac{P_r L}{G_t G_r} \left(\frac{4\pi r_1}{\lambda} \right)^\eta + \frac{P_r L}{G_t G_r} \left(\frac{4\pi r_2}{\lambda} \right)^\eta \leq \frac{P_r L}{G_t G_r} \left(\frac{4\pi d}{\lambda} \right)^\eta \quad (4.4)$$

Where r_1 is the distance between the source and the relay node, r_2 is the distance between that relay node and destination and r_1 , r_2 and d lie within range r_s . Then Equation 4.4 can be simplified to,

$$r_1^\eta + r_2^\eta \leq d^\eta \quad (4.5)$$

The region between source and destination for which Equation 4.5 is satisfied then defines a gain region. The term gain is used simply to reflect the fact that the circumstances described above can lead to a lower power consumption than the direct transmission route.

The exact boundary and the resulting gain region shape for which a two-hop route from source to destination reduces the total transmit power is then determined by the path loss exponent η .

The simplest gain region can be defined by assuming a model based on free space propagation which is line-of-sight based with the path loss exponent $\eta = 2.0$. In this case, the signal strength observed at the receiver is inversely proportional to the square of distance, and Equation 4.5 becomes

$$r_1^2 + r_2^2 \leq d^2 \quad (4.6)$$

Equation 4.6 defines a gain region which is represented as a circle of diameter equal to the source-destination distance as shown in Figure 4.5. Outside the region a relay node will not be selected because the total transmission power required for a 2-hop route between source and destination would exceed that for any relay node selected within the gain region and for the direct source-destination transmission.

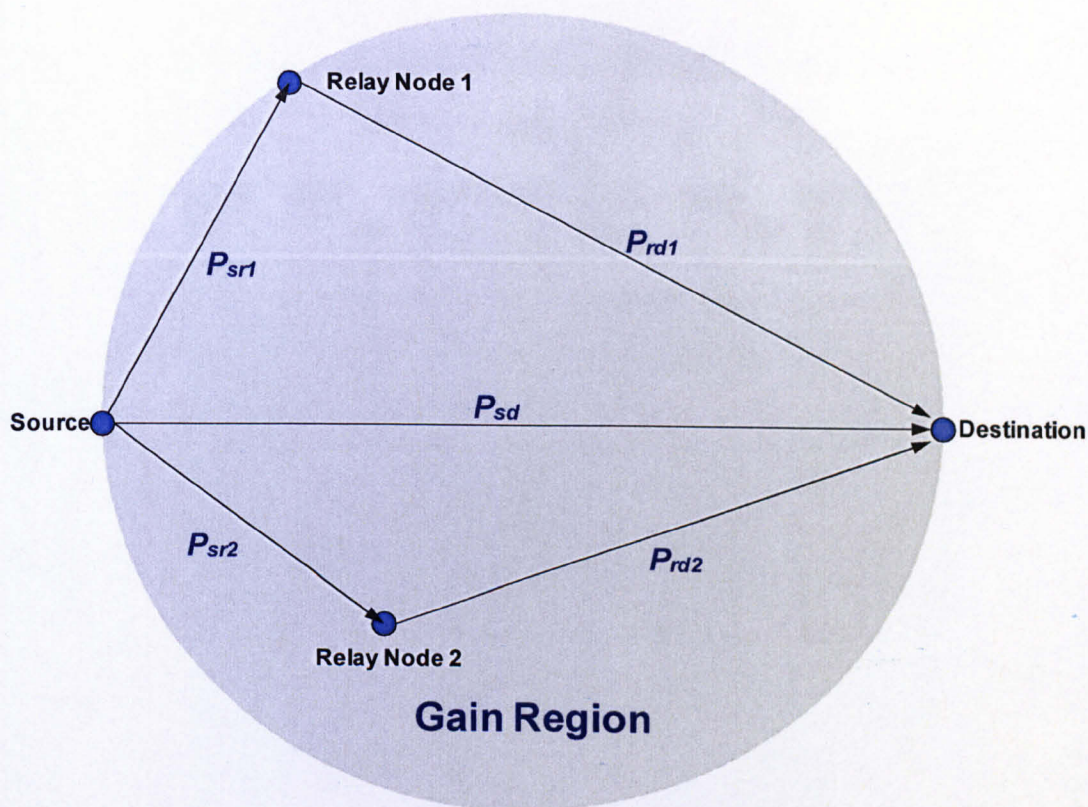


Figure 4.5. Concept of a Gain region

In Figure 4.5, P_{sd} , P_{sr} and P_{rd} are the transmission power from the source to the destination, the source to the relay node and the relay node to the destination respectively. Hence for a FSPL model the gain region defines a region in which transmission from source to destination via a single relay node would provide lower power consumption than direct transmission. Utilising relay node 1 which lies at the edge of the gain region will give the same total required transmission power as that for the direct transmission between source and destination, while utilisation of any other nodes within the gain region, such as relay node 2, would require a lower total transmission power than the direct route.

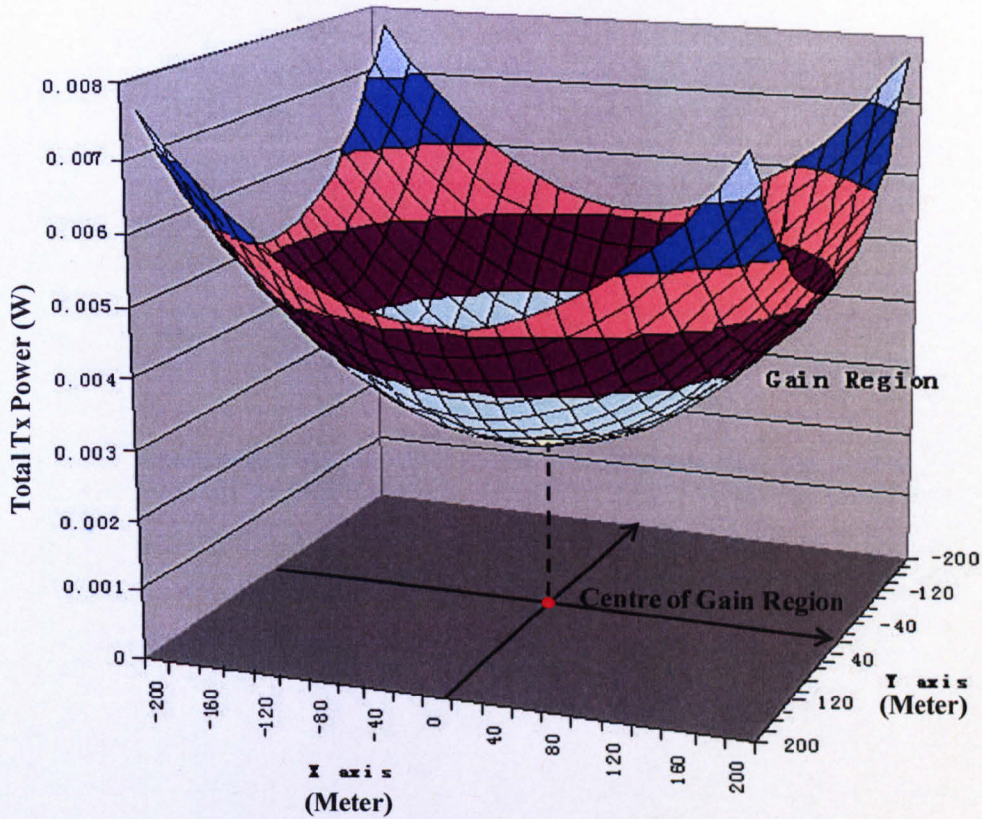


Figure 4.6. Total Transmission Power in the Gain region 3D

Figure 4.6 illustrates the variation with relay node position of the overall power required for a simple two-hop network. The source and destination are assumed to be 400 meters apart and the power required for the direct link between them is 5mW with the path loss exponent of $\eta = 2.0$. Since the 400m distance between the source and destination nodes exceeds the maximum distance requirement according to the 802.11 standard, a relay node between them is then required. The lowest total transmission power or the maximum gain is achieved for a relay node at the position of the centre of the direct line between source and destination which is also the centre of the gain region. The overall power reduction can be evaluated along the directions from the centre of the gain region, which corresponds to the region where hops can decrease the required transmit power. The required transmission power increases rapidly with increasing distance of the relay node from the centre of the gain region. A 2D representation of the total transmission power in the gain region under the same network condition as Figure 4.6 is shown in

Figure 4.7 below. The power required for a relay node positioned in the network is then determined by the distance between the node and the centre of gain region

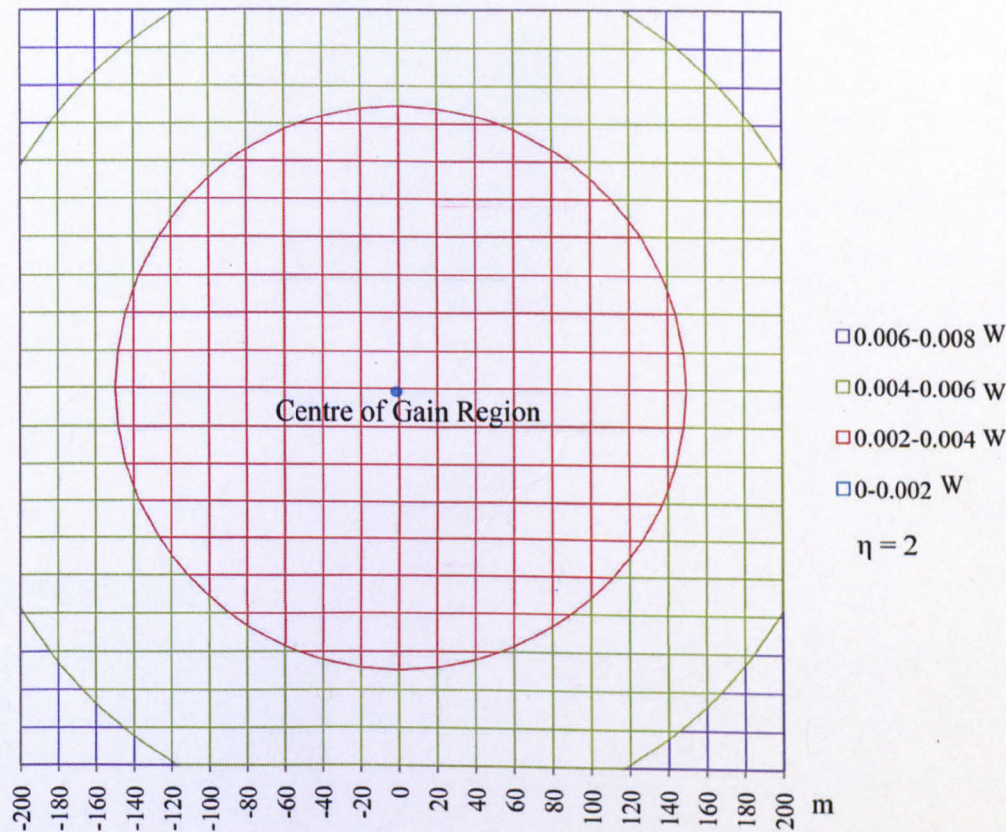


Figure 4.7. 2D Representation of Total Transmission Power in the Gain region

Figure 4.8 shows the gain regions calculated using Equation 4.5 for three different path loss exponents, where the distance between source and destination has been normalized to 1. For larger path loss exponents, the gain region is elongated perpendicular to the direct link direction between source and destination. In Figure 4.8 high path loss exponents which would not be found in practice have been selected to demonstrate the general dependency of the shape of the gain region on the path loss exponent.

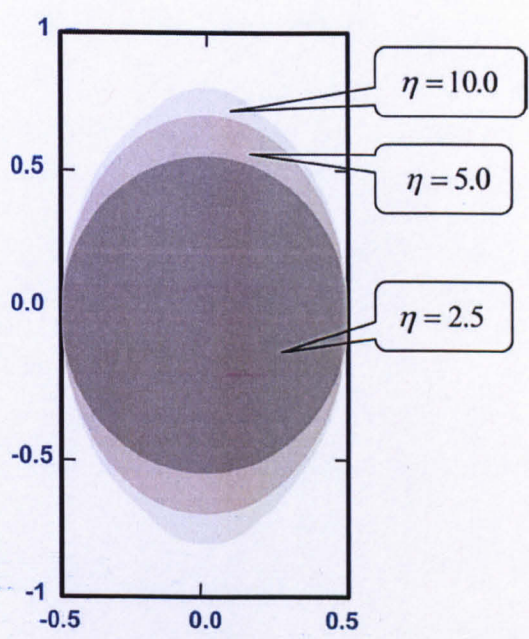


Figure 4.8. Gain Regions with various path loss exponents η

4.3.2 Relay Region

Having defined the gain region, a natural extension is to specify a relay region. This can be defined as the overlap of the area covered by a circular region of radius equal to the transmission range and the gain region. The relay region is then shown as the shadow area in Figure 4.9. All nodes falling within the relay region will constitute the source node neighbour table and may, if path loss and battery life permit, be used as a relay node.

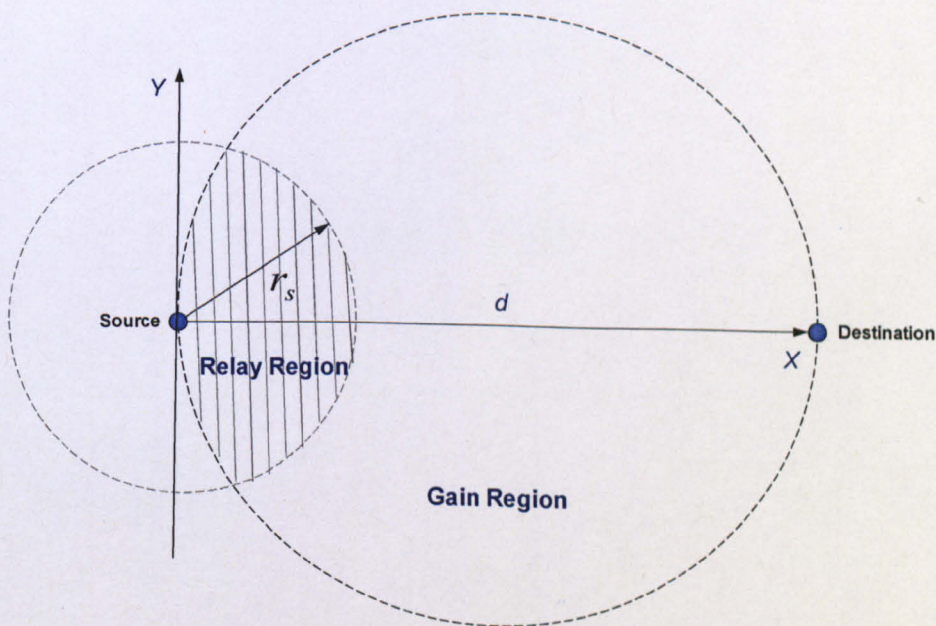


Figure 4.9. Relay Region

To minimise the energy consumption for a given route, the number of relay nodes should be limited, because the processing energy at each relay node is a significant contribution to the total energy consumption. The transmission range determines the maximum distance for each hop but there should also be a minimum distance in order to limit the hop count. One approach to defining a modified relay region is that the first relay node falls within a distance r_d from the destination where

$$r_d = (n-1) * r_s \quad (4.7)$$

Equation 4.7 implies that $n-1$ hops are possibly left from the relay region to the destination if we assume a minimum hop count of n . The modified relay region is shown as the shadow area in Figure 4.10.

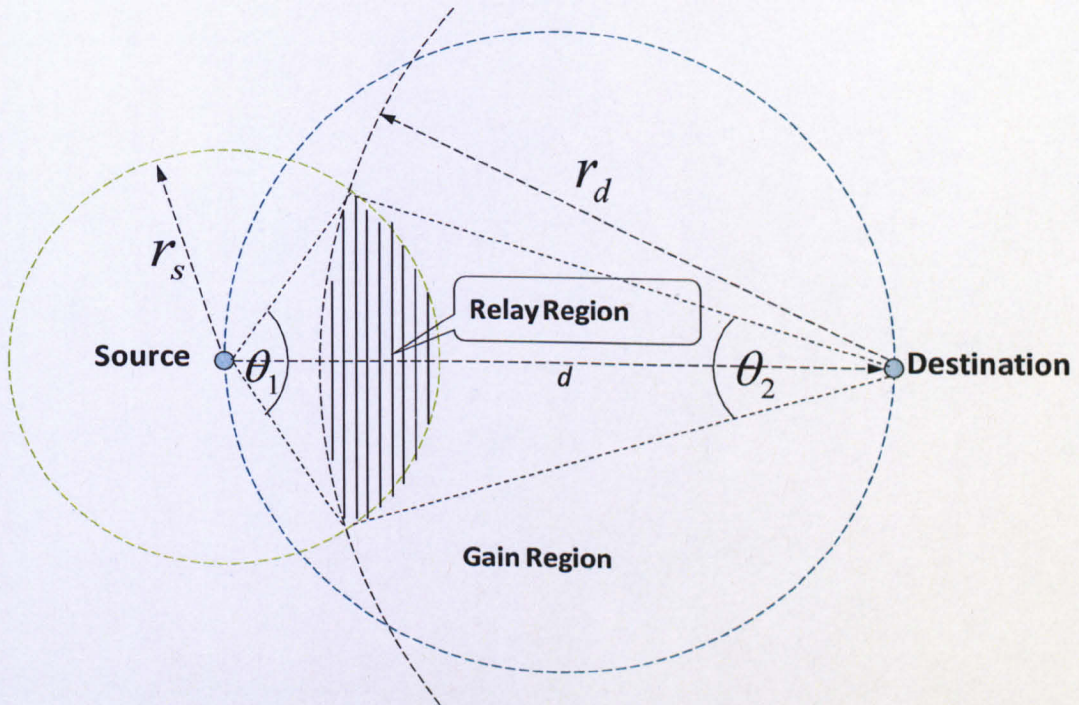


Figure 4.10. Relay region for Multi-hop Network

Those nodes lying within the relay region would constitute the source node relay table. For multi-hop routes, the process can be repeated by assuming the relay node acts as the new source node as illustrated in Figure 4.11 for a four hop network scenario. Three gain regions and relay regions have been defined by r_{d1} , r_{d2} and r_{d3} respectively.

$$r_{d1} = 3r_s \quad (4.8)$$

$$r_{d2} = 2r_s \quad (4.9)$$

$$r_{d3} = r_s \quad (4.10)$$

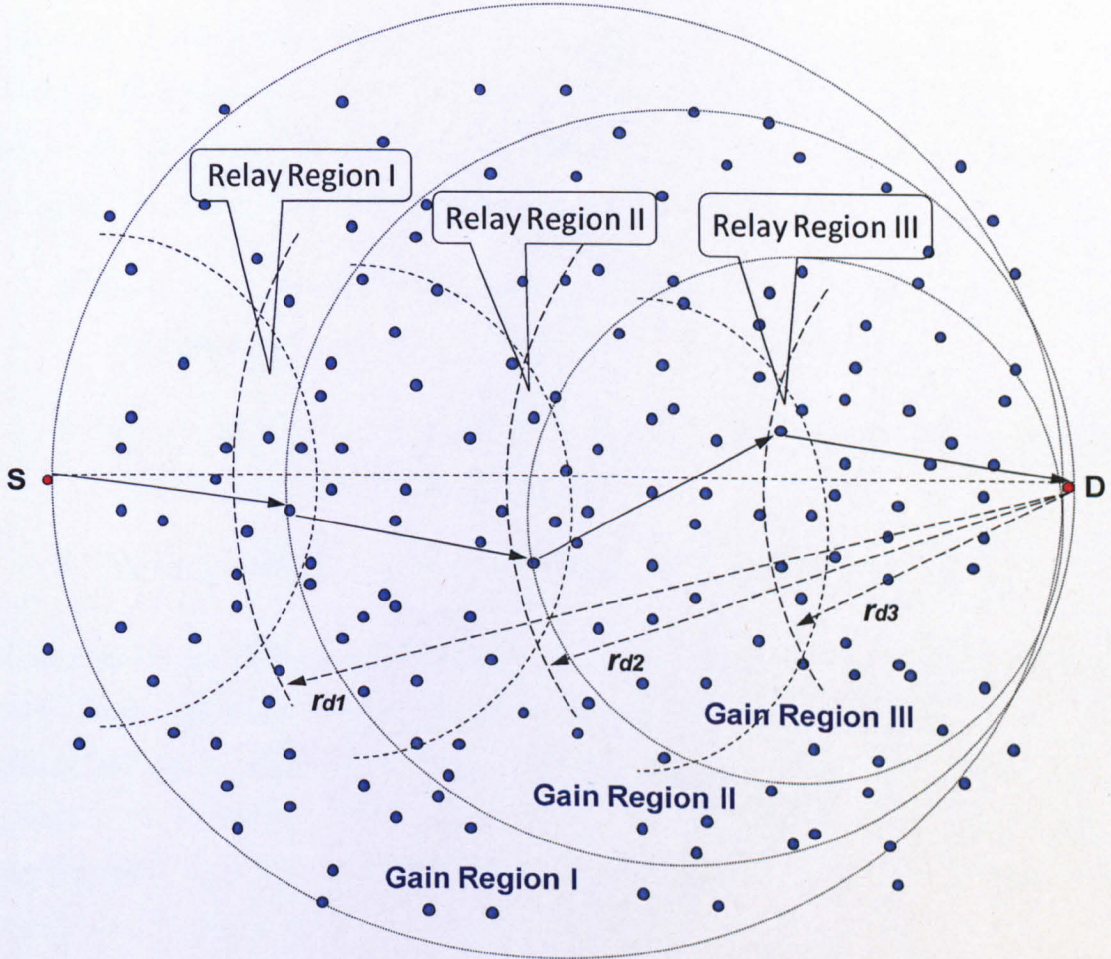


Figure 4.11. Multi-hop Network Example

4.4 Energy Efficient Relay Node Selection

The energy efficient routing protocol aims to minimize the total energy consumed in forwarding a packet from source to destination. Minimum-energy routing can exploit path loss awareness by forwarding traffic using a sequence of low power transmissions. Having established a process to define a region in which acceptable relay nodes may be found, the process of selecting a node within that region is now discussed. Within the relay region, a relay node will be selected to minimise the total transmission power or maximise node lifetime.

The model assumes that all nodes are aware of the location and battery power of neighbour nodes lying within the transmission range, and of the actual path loss to those nodes. This information is gathered through the Hello messages sent periodically through an enhanced signalling process system which will be discussed in details in chapter 6. When a packet needs to be forwarded to the destination node, the source node firstly looks for the destination node within its neighbour table. If the destination node is not in the neighbour table, then a node within the source node's relay table must be selected. The metrics listed below are used to select the relay node.

- Location coordinates determine the distance from the source node to the potential relay node and from the relay node to the destination.
- The actual path loss between source and relay node which also determines the required transmission power of the source.
- The relay node battery level which determines its remaining life time.

Although the gain region can be obtained from the analytical solution based on an ideal FSPL model, the path loss exponent η between any nodes is actually arbitrary and this determines the required transmission power between nodes assuming a fixed receive power level. In order to reduce the total power consumption of the route, links with a smaller path loss are preferentially selected, however the general constraint of minimising the hop count must also be considered.

Mobile node lifetime is constrained by battery power which makes energy efficiency a critical issue. The proposed protocol can either minimise the total power consumption of the route or maximise the life-time of the nodes. The route lifetime can be expressed as the minimum of the lifetimes of its constituent links.

With these considerations in mind, three possible route selection techniques have been implemented through the use of different metrics and criteria to estimate the link cost.

- Position-based routing which purely uses location information for route determination.
- Power-aware-based routing tries to minimise the total power consumption of the route.

- Battery-life-based routing tries to maximise the life-time for the route and sustain for as long as possible nodes with low battery level as potential relay nodes in the network.

4.4.1 Power Aware Based Routing

For power-aware-based-routing, link cost is calculated locally by the current forwarding node using a sum of the power of the known links and the predicted power requirement of unknown remaining links:

$$P_{(p)} = P_{pt} + P_{pn} \quad (4.11)$$

where $P_{(p)}$ is the link power for a candidate node. P_{pt} is the required transmission power from the current node to the candidate node within the relay region which is determined from the actual path loss between them obtained through a Hello message procedure. P_{pn} is the potential required transmission power which is determined by the distance between the candidate relay node to the destination. The procedure used to determine this value is as follows. The maximum transmission range r_s of each node is constrained by the limitation of maximum transmission power. The minimum possible number of hops for the remaining distance can then be predicted as:

$$h_n = \text{roundup}(d_n / r_s) \quad (4.12)$$

where h_n is the roundup integer value for remaining hop count, d_n is the remaining distance to the destination.

Hence the potential power consumption for that distance is calculated using a predefined reference transmission power P_{ref} which is used to estimate the potential required power for each remaining relay node multiplied by the hop count:

$$P_{pn} = h_n * P_{ref} \quad (4.13)$$

In Equation 4.13, the predefined reference transmission power P_{ref} is calculated by using Equation 4.3 based on the average hop distance d_n/h_n for the remaining hops and the FSPL model.

4.4.2 Battery Life Based Routing

Battery-life-based routing can be undertaken by examining the remaining battery level in comparison with the full battery capacity of the mobile nodes.

Battery capacity is determined by the amount of electrical energy the battery can deliver over a certain period of time and is measured in Ampere hours (Ah) when discharged at a uniform rate over a given period of time. When multiplied by the average battery voltage over the discharge cycle the battery capacity becomes watt-hours (Wh). If a potential relay node has a remaining battery level of B_{remain} (Wh) then the remaining working hours or life-time can be calculated by the equation below:

$$T_{remain} = B_{remain} / p \quad (4.15)$$

where T_{remain} is the remaining life-time of the battery and p is the transmit power required to reach the next relay node or destination.

The link cost, $T_{(b)}$, is described as:

$$T_{(b)} = \arg \min \{T_{bt}, T_{bn}\} \quad (4.16)$$

where T_{bt} is the life-time of the link between the current node to its candidate node and is determined by dividing the remaining battery capacity by the transmission power required to reach the candidate node which can be obtained through received Hello messages. T_{bn} is the life-time of the link from the candidate node to next relay node which is calculated by dividing the remaining battery capacity B_n of the candidate nodes by the reference transmission power P_{ref} :

$$T_{bn} = B_n / P_{ref} \quad (4.17)$$

Once the decision to select the first relay node has been made, the second gain region will then be defined between the first relay node and the destination. The subsequent relay nodes can be chosen by defining a gain region between the current relay node and the destination.

4.5 Simulation and Results for Three-hop Scenario

To simplify the simulation analysis, the network is designed with three hops. Results for a larger number of hops are achievable using the same techniques as in this three-hop network. The proposed routing scheme for the network as shown in Figure 4.12 is modelled and implemented on the OPNET Modeler simulation platform. 240 nodes are randomly deployed on a network of 350m by 350m square. Each node has been assigned a random battery level and a random path loss exponent in the range 2-4, to neighbour nodes. The antenna gains and system loss in (4.3) are set to unity. A frequency of 2.4 GHz is assumed corresponding to the frequency band used in WiFi applications. The gain regions used in the routing protocol are determined as discussed above.

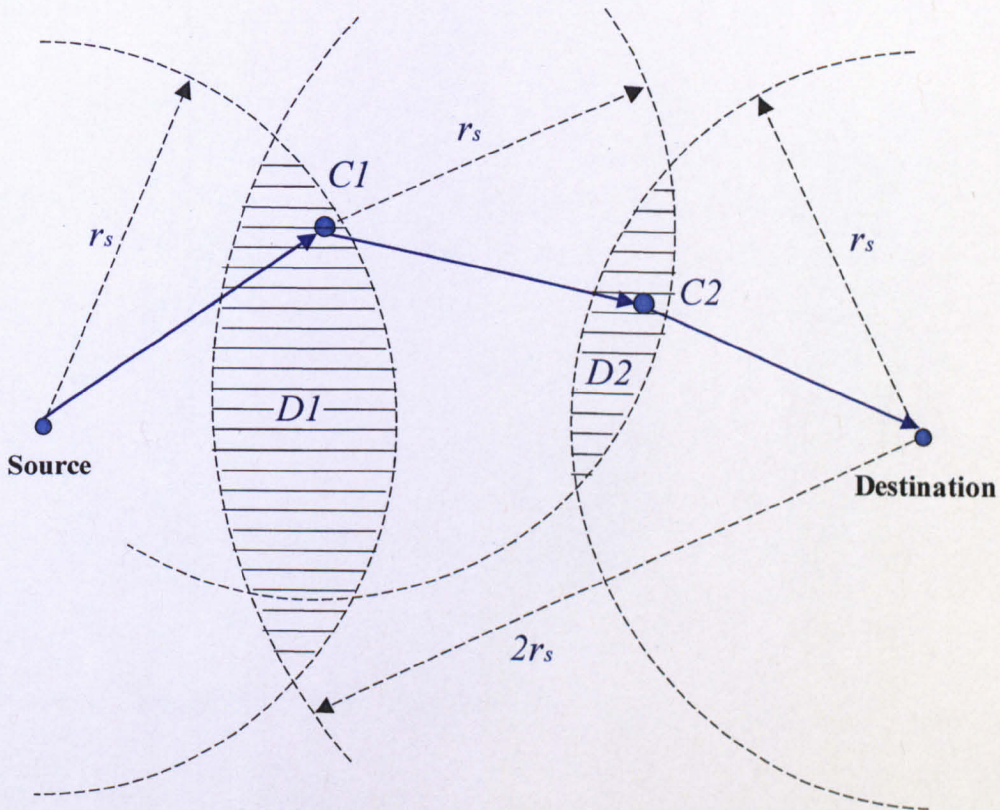


Figure 4.12. Three-hop network

In order to estimate the performance of the proposed routing protocol, Simulation results were obtained from 30 different path loss exponent assignments. According to the standard, the maximum transmission range for WiFi equipment in open space is about 300 meters and that distance may be reduced to 100 meters in an indoor office environment. An initial maximum transmission range of 140m was used for all the nodes which determines the minimum number of hops for the selected route to be 3.

Routes with more hops could be enforced by using a smaller transmission range or increasing the source to destination distance if required. In order to demonstrate the advantage of the proposed protocol, its performance is compared to a straight-line ODF (Optimum-Distance Forwarding) route based on a conventional geographic routing protocol. The ODF route uses equal distance for each hop and the hop count is determined by the distance between the source and destination and the maximum transmission range. In the results presented in Figures 4.13 to 4.17, the transmission power and route life-time are based on an average of the results obtained from the 30 simulation results.

In the following simulations, the transmission range is varied from 130 to 180 meters to analyse the performance of the proposed routing protocol under different range conditions.

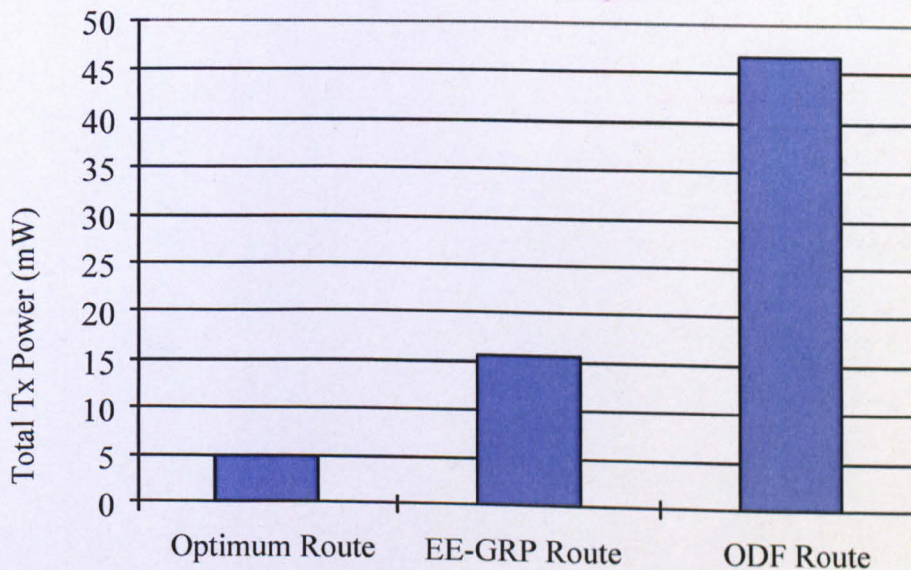


Figure 4.13 Comparison of total transmission power (140m range)

Figure 4.13 shows a comparison of the total transmission power for the selected route determined by the power-aware-based routing scheme, the ODF route and the Optimum Route which has the lowest total power consumption obtained through analysis of all possible end-to-end routes which could be achieved if each node is aware of the link loss to all other nodes. It can be observed that in the ODF route the average total transmission power from 30 simulations is 46.73 mW. However, by introducing the

proposed protocol, the total transmission power of the selected route is decreased to 15.51 mW which is 33.2% of that for the ODF route.

Comparison of the route life-time for the selected route determined by the battery-life-based routing scheme and for the ODF route is presented in Figure 4.14. The life-time of the ODF route is 3.06 hours whereas that for the selected route has a life-time of 42.4 hours. The increased life-time for the selected route implies an enhanced routing performance provided by the proposed protocol. The significant improvement in route life-time arises because under this protocol a node with high battery level is preferentially selected even though the total route transmission power may not be the lowest under the power-aware based routing protocol. A node with high remaining battery capacity has a greater chance of being selected even if its transmission power may not be the lowest.

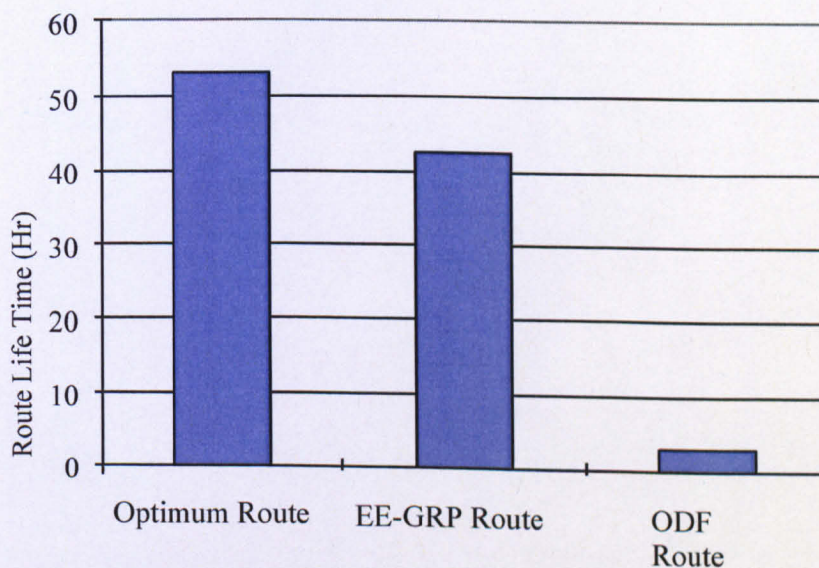


Figure 4.14 Comparison of route life time (140m range)

The maximum permitted transmission power determines the transmission range of a mobile node and hence the maximum distance for each hop. The ODF route is not affected by the maximum transmission range if the possible hop count between the source and destination is not affected and remains the same. This is because the required equal distance for each hop won't be affected by the change of maximum transmission range. The ODF route will select the same relay nodes at the same locations under the same hop count. However, the selected route may change as the distance for each link

of the selected route changes according to the transmission range. If the maximum transmission range increases, the size of the relay region between the source and destination node also increases as illustrated by the relay region $\alpha 2$ shown in Figure 4.15. The increased size of this region provides more candidate nodes and a greater possibility of finding a better route. In effect a relay node for minimised power consumption or maximised lifetime would be selected from a larger number of candidate nodes. The position of the selected relay node then affects the size of subsequent gain regions and the number of candidate nodes within those relay regions.

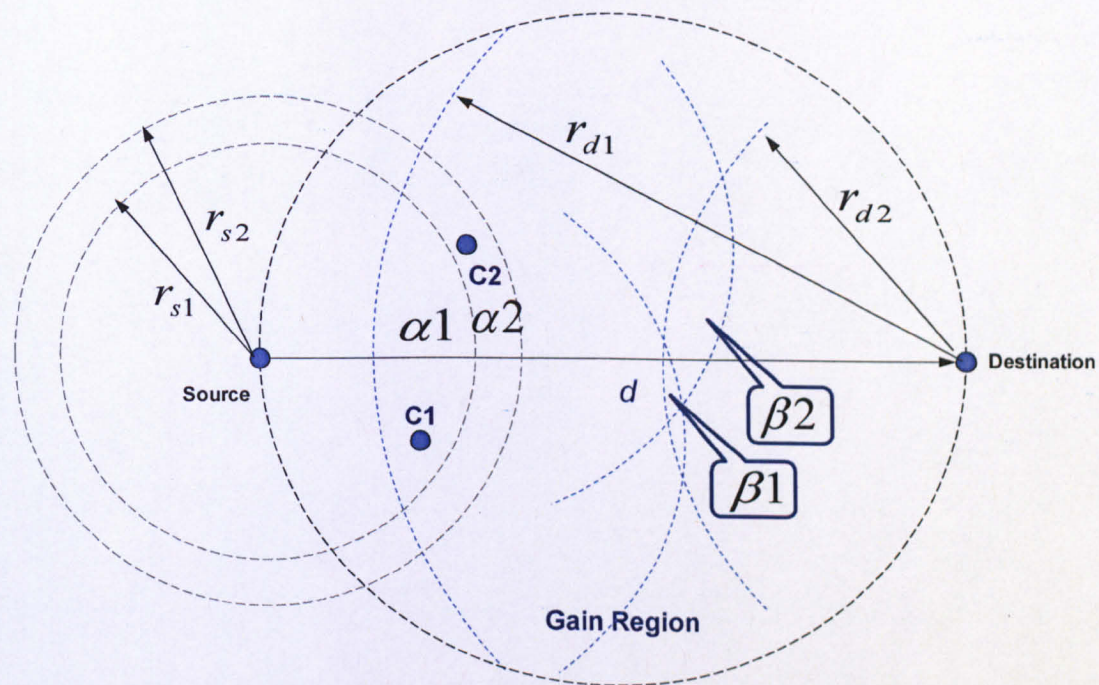


Figure 4.15 Increased Relay Region Size by Increased Tx Range

As shown in Figure 4.15 with an increased size of relay region $\alpha 2$ caused by the increased transmission range, there will be a higher possibility to select a relay node which is closer to the destination. In Figure 4.15, the position of the relay node $C1$ which is selected under a smaller transmission range r_{s1} determines the relatively small size of relay region $\beta 1$. In some cases with small transmission range r_{s1} , the resulting small size of the relay region $\beta 1$ may lead to there being no candidate nodes within it. Relay node $C2$ selected under transmission range r_{s2} defines an increased size of relay region $\beta 2$ which would contain more candidate nodes for relay selection.

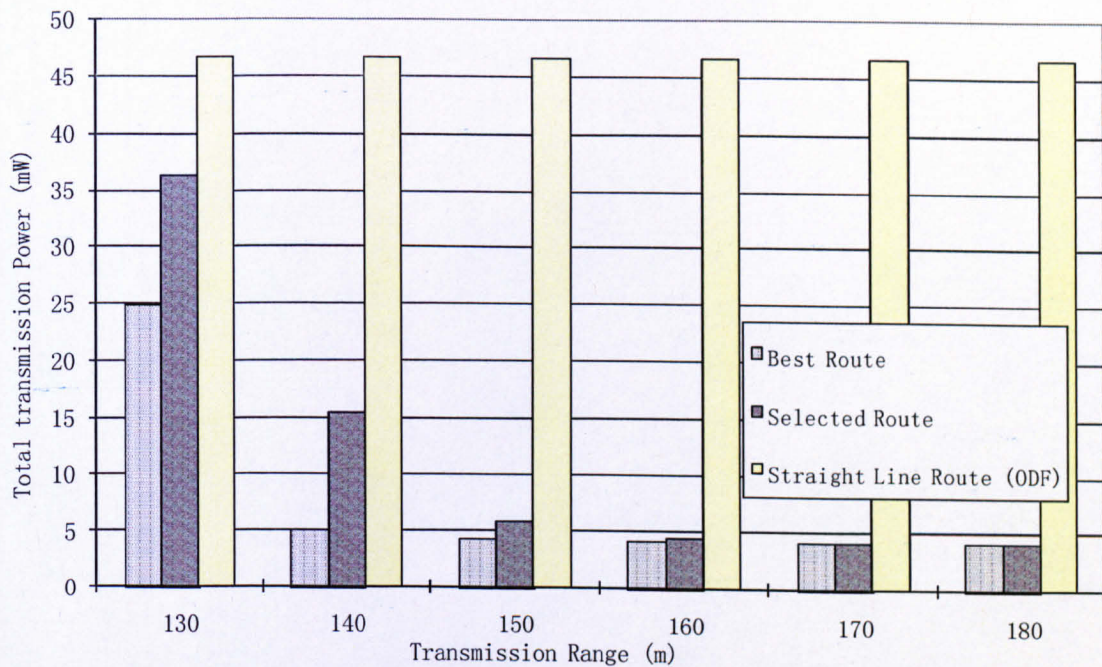


Figure 4.16 Comparison of total transmission power with different transmission range

For a source to destination distance of 350m and a three hop route, Figure 4.16 shows how increasing the transmission range lowers the total transmission power requirement. The power reduction arises from the increased choice of nodes within the gain region. The choice of a relay route lying closest to the straight-line route between source and destination does not on average lead to a lower power transmission as the path loss between these nodes can be very high. For the maximum transmission range of 170 m the required transmission power utilising power-aware based routing is 9% of that required using the straight line route (ODF). As can be observed from Figure 4.16, with the increment of transmission range the total power consumption of the selected route reduces as the transmission range increases from 130m to 150m. When the transmission range is greater than 150 meters, the results for the selected route are very close to those of the optimum route because the sizes of the gain region becomes large enough for routes with the lowest or nearly the lowest power consumption to be found.

Figure 4.17 shows how increasing the range affects the route lifetime. The increased node choice leads to an increase in the link lifetime and as with the analysis of power transmission, a significant improvement over the lifetimes achievable for the ODF routing is obtained. However, route lifetimes for the ODF route solution are constant

with transmission range changes because its route remains the same under three hops. Relay nodes with longer battery life were found within the larger relay regions determined by the increased transmission range.

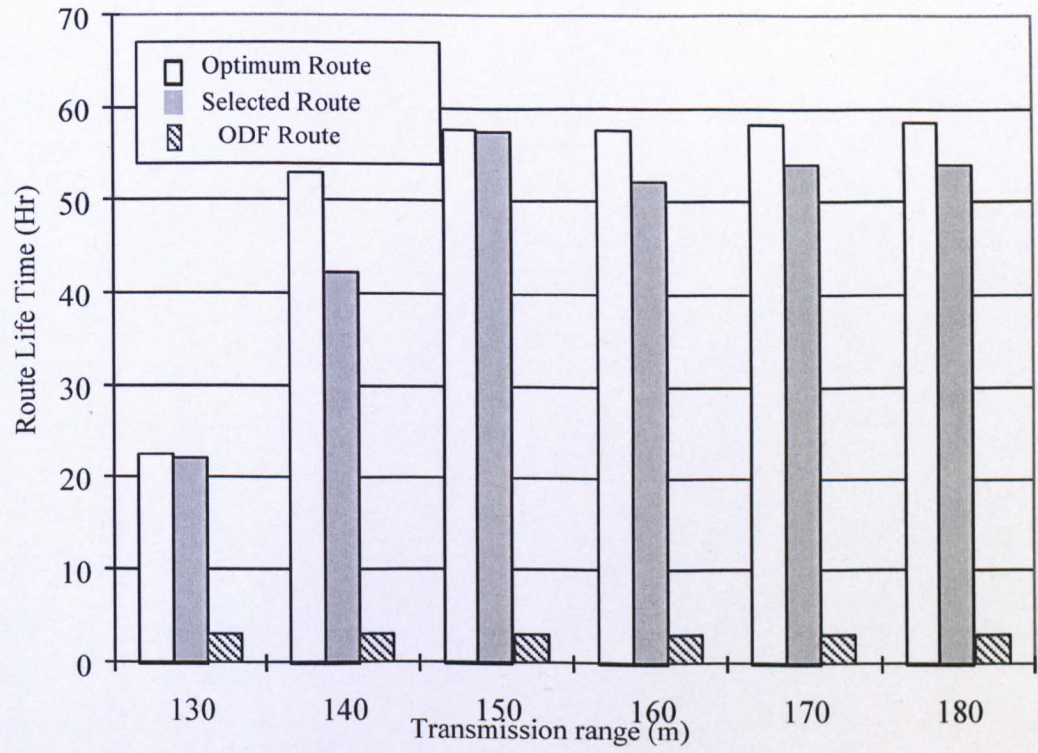


Figure 4.17 Comparison of route life time with different transmission range

4.6 Summary

This chapter introduced the development of an energy efficient geographic routing protocol. For comparison several conventional forwarding strategies were discussed together with their relative advantages and disadvantages. The concepts of gain region and relay region were described to exploit the novel features of the proposed energy efficient geographic routing protocol in which candidate relay nodes are defined.

Based on the framework described in Chapter 3, the proposed routing protocol was designed and implemented within OPNET to simulate the energy efficient operation. The routing performance has been analysed in terms of total transmission power and route life time to show the benefit of the energy efficient geographic routing protocol. The proposed routing protocol is shown to provide both power and route lifetime advantage over several established protocols.

Chapter 5 Development of Enhanced Energy Efficient Geographic Routing Protocol

5.1 Routing Protocol Improvement through Relay Region Modification

The routing approach EE-GRP discussed in the previous chapter minimises the hop count but can lead to small relay regions. As the relay nodes are selected from within the relay region, the size of the relay region determines the number of nodes which are eligible to act as a relay. A better relay node with lower relay energy consumption can be selected if the number of candidate nodes is increased through use of a larger relay region. As such a modified technique is now described which seeks to ensure adequate size relay regions are used for each hop and thereby produce a more energy efficient performance through hop count optimisation.

An initial step towards defining a new technique is described with the aid of Fig 5.1 which illustrates a new approach to defining the relay region. In the diagram the relay region is the shaded area formed by the overlapping region created by circles of diameter r_s (the transmission range) drawn from the source node and r_d (defined below) drawn from the destination node.

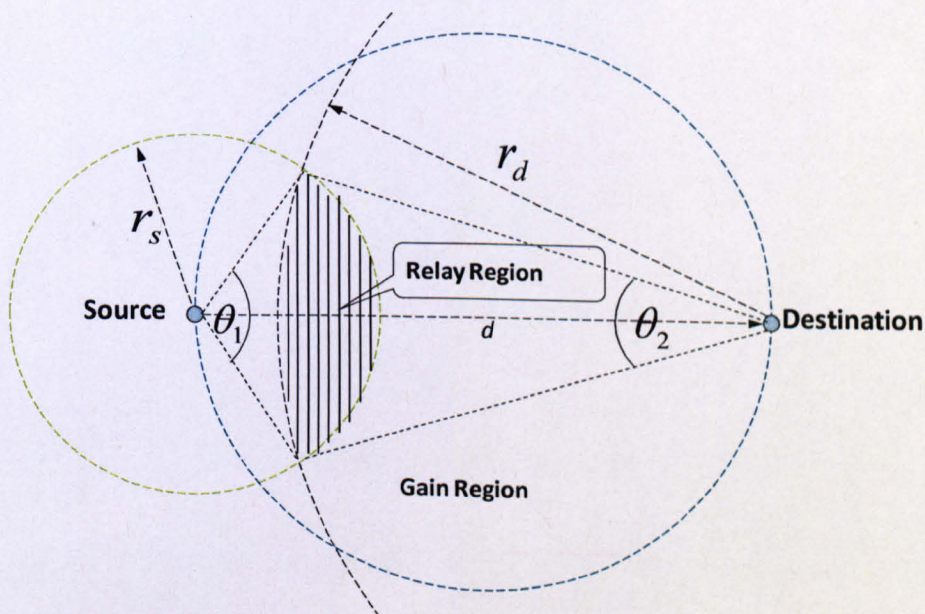


Figure 5.1 Gain region for multi-hop network

r_d is the only unknown metric which will determine the size of relay region. The range for the distance of r_d can be defined as:

$$d - r_s \leq r_d \leq (n-1)r_s \quad (5.1)$$

Where n is the hop count between the source and destination. When r_d equals $(d - r_s)$, the minimum zero size of relay region would be defined. In this case, a relay node would have to lie on the straight line route between the source and destination at a distance r_s from the source. This extreme situation is illustrated in Figure 5.2.

The upper limit of $(n-1)r_s$ arises from the definition of the minimum hop count under $n = \text{roundup}(d/r_s)$. The maximum size of relay region defined by the upper limit is shown in Figure 5.2.

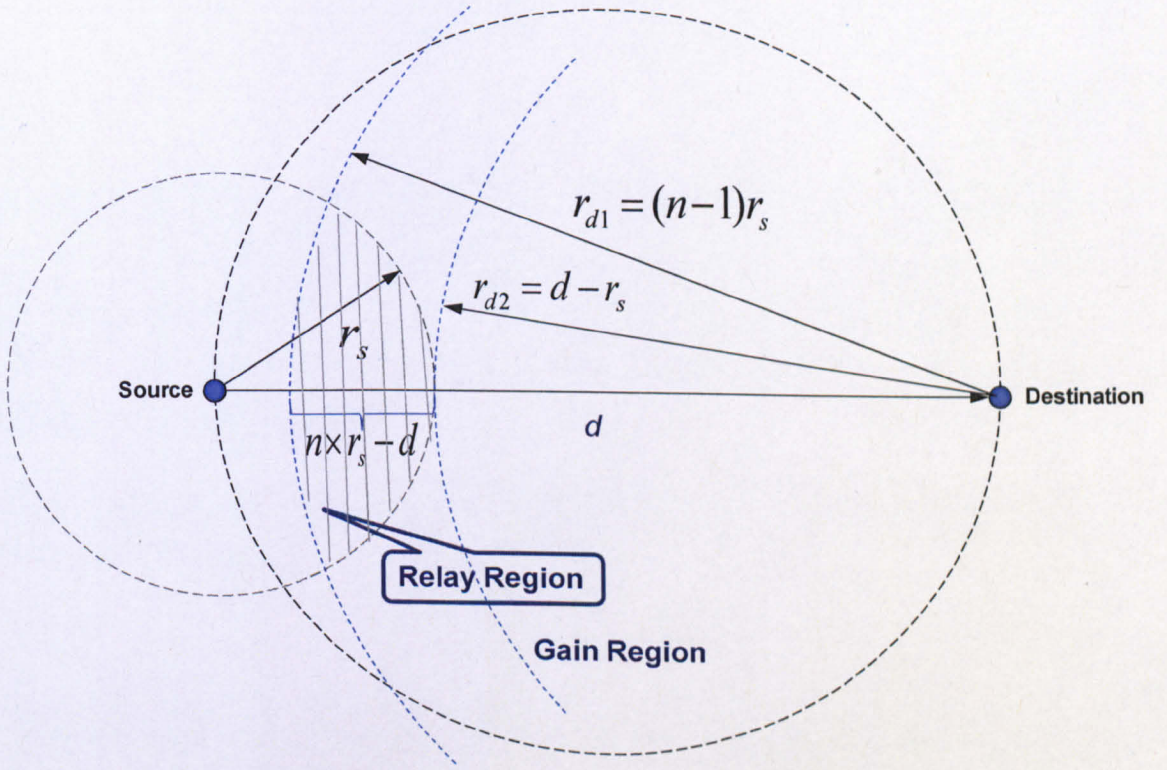


Figure 5.2 Limits of r_d which define the relay region

The size (area) of the relay region shown as the shaded area in Figure 5.1 is given by:

$$S_{relay} = \left(\frac{r_s^2 \theta_1}{2} - \frac{r_s^2 \sin \theta_1}{2} \right) + \left(\frac{r_d^2 \theta_2}{2} - \frac{r_d^2 \sin \theta_2}{2} \right) \quad (5.2)$$

Where

$$\theta_1 = 2 \times \cos^{-1} \left(\frac{r_s^2 + d^2 - r_d^2}{2r_s d} \right) \quad (5.3)$$

$$\theta_2 = 2 \times \cos^{-1} \left(\frac{r_d^2 + d^2 - r_s^2}{2r_d d} \right) \quad (5.4)$$

Then (5.1) can be represented as

$$S_{relay} = \left(\frac{r_s^2 \times 2 \times \cos^{-1} \left(\frac{r_s^2 + d^2 - r_d^2}{2r_s d} \right)}{2} - \frac{r_s^2 \sin \left(2 \times \cos^{-1} \left(\frac{r_s^2 + d^2 - r_d^2}{2r_s d} \right) \right)}{2} \right) + \left(\frac{r_d^2 \times 2 \times \cos^{-1} \left(\frac{r_d^2 + d^2 - r_s^2}{2r_d d} \right)}{2} - \frac{r_d^2 \sin \left(2 \times \cos^{-1} \left(\frac{r_d^2 + d^2 - r_s^2}{2r_d d} \right) \right)}{2} \right) \quad (5.5)$$

However while the above scheme provides a new model for defining the relay region, in this model, the maximum size for the relay regions provides a relay node choice with lower energy consumption for the first hop only. The remaining hops may have extremely small relay regions which can lead to a situation in which there are no available nodes within the region.

The reason why this problem can occur is now discussed. The maximum width of the first relay region is given by:

$$n \times r_s - d \quad (5.6)$$

The problem of a small size being produced for subsequent relay regions can occur when a relay node in the first relay region which is close to the source node is selected. This problem is not significant in three-hop networks, but becomes critical when hop count increases as shown in Figure 5.3. In this figure the first relay region determined by using the criteria defined in Equations 5.1-5.6 is large but the choice of a node lying close to the source in the first region leads using 5.1 – 5.6 to the subsequent regions being too small to support an adequate choice of nodes.

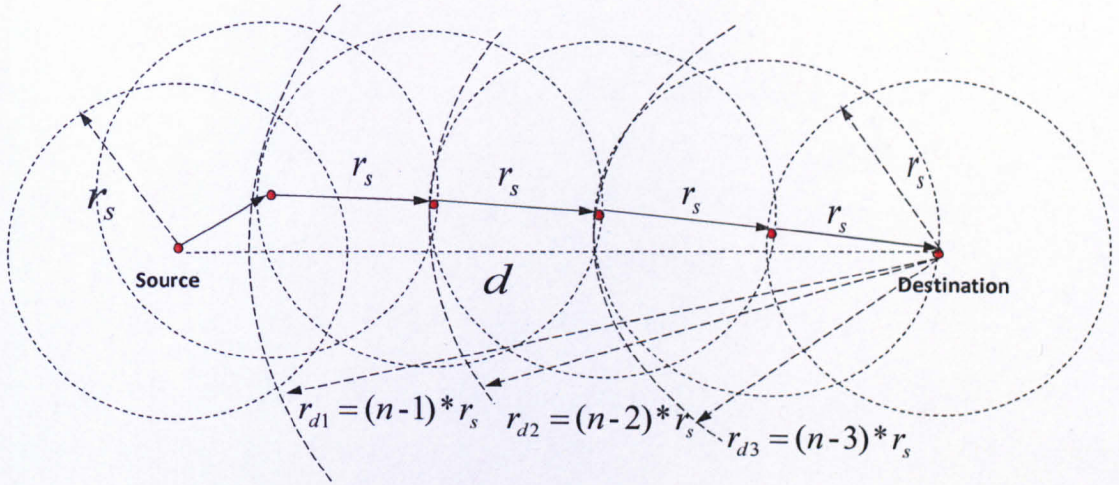


Figure 5.3 Limited Relay Region Size under Minimum Hop Count

In order to achieve the minimised hop count in Figure 5.3, the remaining hops have to satisfy the condition that the distance for each hop is approximately the maximum transmission range. This can only be satisfied in a free space scenario under FSPL model. When a non-FSPL model is applied, the radio signal is degraded more heavily and the maximum transmission range is not achievable. The requirement to minimise the hop count can therefore lead to a relay region which is very small and there may be no candidate nodes within the relay region. If minimum hop count fails, due to the above problem, the hop count can be increased by 1 and the process of defining a region is then undertaken with the new hop count. With an increased hop count, the defined relay region is larger which increases the number of candidate nodes as shown in Figure 5.4. However on the negative side the hop count has now increased.

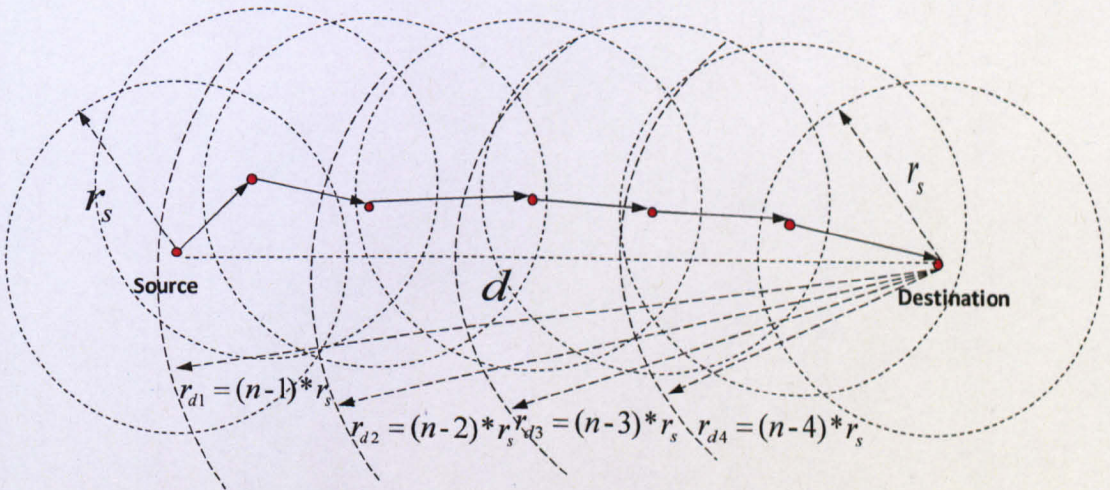


Figure 5.4 Solution to Limited Relay Region Size Problem - Step I

5.2 Optimisation for Relay Region Size

Given the problem just discussed an alternative method of defining the relay region is now proposed. In order to ensure that an adequate number of potential relay nodes will exist for each hop, a system of constraining the size of the relay regions is proposed. The regions are defined such that their areas will provide reasonable probabilities that adequate potential nodes exist for all expected node densities.

For multi-hop routes, the ideal scenario is that each link has the same distance of d/n as shown in Figure 5.5, where d is the distance between source and destination nodes and n is the minimum number of hops under transmission range r_s .

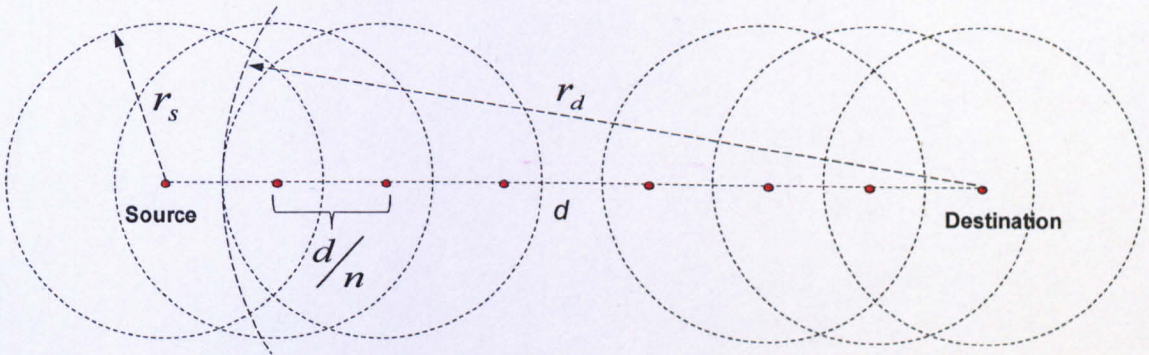


Figure 5.5 Optimised Size of Relay Region with n hops

Based on Figure 5.5, the optimal distance from the destination r_d for each hop can be defined as:

$$r_d = (\text{remaining_hop} - 2) * d_{av} + r_s \quad (5.7)$$

Where

$$d_{av} = d / n \quad (5.8)$$

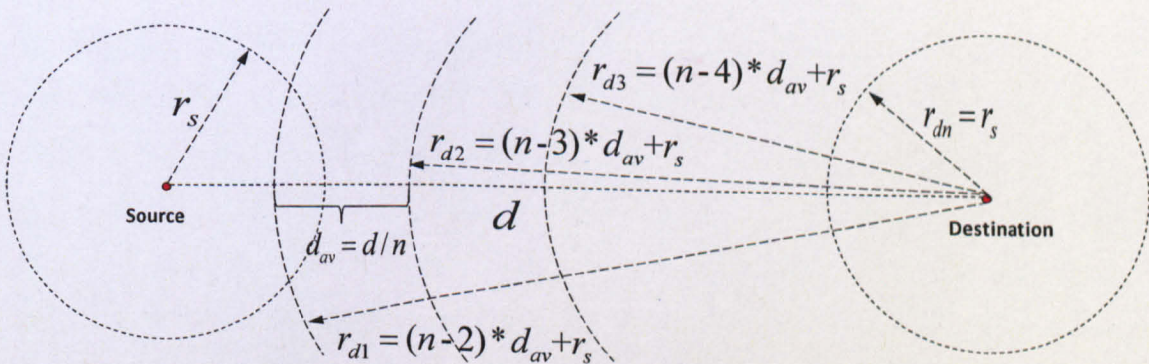


Figure 5.6 Distance from destination for each hop

As shown in Figure 5.6, the new condition for the distance requirement of each hop to the destination is applied which defines a positive forward process for each hop to guarantee packet delivery under the remaining hop count. For example, if the source and the destination nodes are 300m from each other, the maximum transmission range is 90m, the minimum hop count and d_{av} can be calculated as:

$$n = \text{roundup}(300m/90m) = 4 \quad (5.9)$$

$$d_{av} = 300m/4 = 75m \quad (5.10)$$

The d_{min} which is the minimum forward distance for each hop can be obtained:

$$d_{min} = 75 - (90 - 75) = 60m \quad (5.11)$$

By defining the minimum hop distance for each hop, the relay region can maintain a reasonable value.

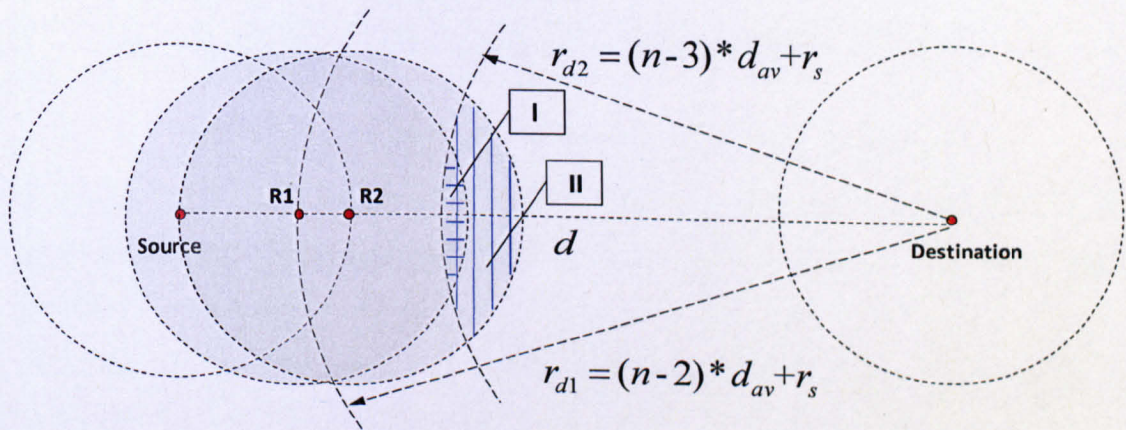


Figure 5.7 Size Control Mechanism for Relay Region

To illustrate how this revised model of relay region selection improves the node selection opportunities, in Figure 5.7, region I and II are the sizes for the second relay region when nodes R1 and R2 are selected for the second hop respectively. As these two nodes reflect the extreme choices for nodes within the first relay region (R1 being closest to the source and R2 furthest away) the subsequent relay regions produced using them as source nodes reflect the extremes of possibilities. It can be seen that even the smallest region I still has a reasonable area, although the number of nodes that may be contained in the relay region is dependent on the product of the node density and the region area. Region I has the smallest size and this size has to satisfy the condition that

a certain number of candidate nodes can be found within this region. In the simulation, a minimum of 3 candidate nodes were used for this condition of the relay region.

To illustrate the issue, Table 5.1 shows the calculated relay region size for different hop count and transmission range based on the scenario used in Chapter 4 in which there are 240 nodes in the network, the network physical size is 350X350m² and the distance between source and destination node is 350m. In this scenario the node density is 0.001959 node/m² and under such conditions the minimum relay region area needed to provide an average of three nodes is 1531 m².

Hops \ Range	70 m	80 m	90 m	100 m	110 m	120 m
3	---	---	---	---	---	288 m ²
4	---	---	171 m ²	1974 m ²	4887 m ²	8689 m ²
5	---	1302 m ²	3795 m ²	7169 m ²	11332 m ²	16236 m ²
6	1546 m ²	4046 m ²	7376 m ²	11464 m ²	16270 m ²	21774 m ²
7	3382 m ²	6437 m ²	10239 m ²	14753 m ²	19957 m ²	25837 m ²
8	4972 m ²	8370 m ²	12480 m ²	17277 m ²	22748 m ²	28883 m ²

Table 5.1. Size of Relay Region under Different Tx Range and Hop Count

When the transmission range equals 120m, the source node may theoretically reach the destination within 3 hops and a candidate relay node may be found within a relay region of 288m² size. However due to the low density of the nodes and NFSPL, the source node may fail to find a relay node in the relay region under such network conditions. Hence, 3 hops for 120m transmission range in the network are not achievable and 4 hops would be the optimised hop count in this case. When the transmission range was 70m, 5 hops is the minimum theoretical hop count and six hops would provide a relay region area which satisfies the minimum area requirement to support three nodes. However, while based on node density, a minimum area which should contain three nodes can be defined, it was shown during numerous simulation runs (varying node distributions) that owing to the random distribution of nodes, occasionally the number of nodes within the defined region fell below the required number and the experimental simulation results actually showed that the optimised hop route can be found when the relay region size is no less than 3000m² which in the latter case of a 70 m transmission range would require 7 hops as the optimised hop count.

Whether a route using a small hop count can be implemented or not depends on the difference between $n_{min} * r_s$ and d , which is determined by the following metrics.

- Distance between source and destination
- Maximum transmission range of each mobile node
- Node density for the network
- Distribution of the nodes
- Path loss condition of the network

Instead of using maximum-distance forwarding to achieve a minimised number of hops, an improvement to the protocol proposed in this chapter determines an optimal number of hops based on the above metrics and applies the steps below to optimise the route power consumption:

- A determination of the minimum hop count based on source to destination distance and transmission range.
- A determination of the optimal number hop count n_{opt} based on node density

Energy efficient routing protocol is launched in response to the requirements for improved energy saving on selected route.

Figure 5.8 shows the flow chart of the enhanced energy efficient geographic routing protocol EEE-GRP routing process. Firstly, the source node or the current node collects the network parameters such as network physical size, number of participating nodes (and so calculates node density), maximum transmission range and path loss conditions between neighbour nodes.

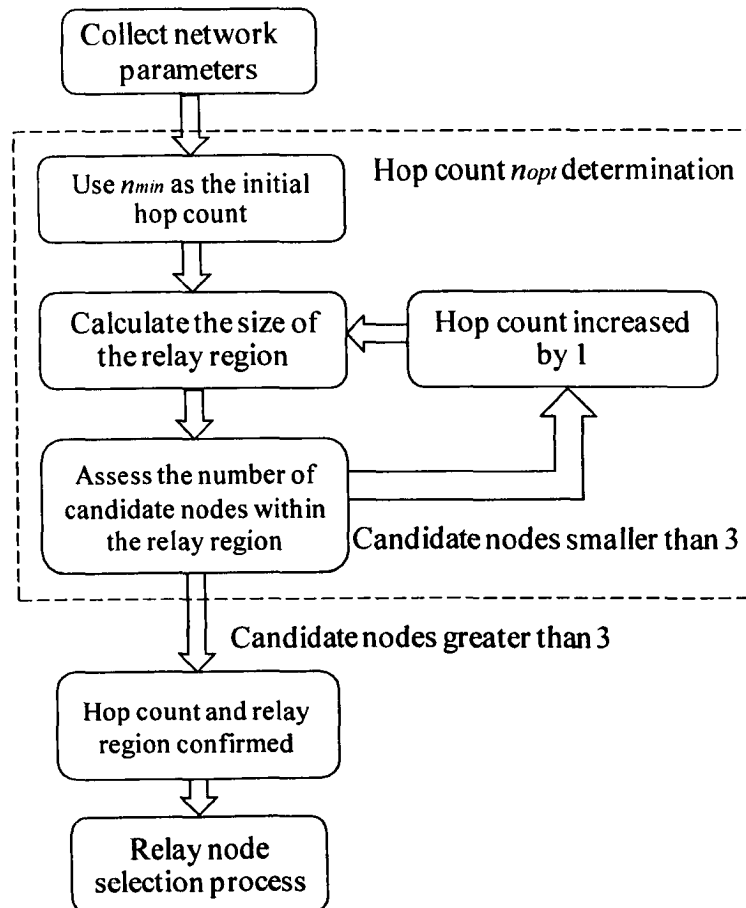


Figure 5.8 Flow Chart of Routing Process

Secondly, an optimised hop count between the current node and the destination node is then calculated based on the previous collected network parameters.

The EEE-GRP protocol will try to use $n_{min} = \text{roundup}(d/r_s)$ as the optimised hop count initially. The main criterion is the number of candidate nodes within a defined relay region which is determined by the optimised hop count. By using the network parameters collected in the first step. If using n_{min} as the n_{opt} could not provide a reasonable size for the relay region, $n_{min}+1$ will be used for the n_{opt} . A larger size for the relay region then can be defined which will be evaluated for the number of candidate nodes within the region. The increase of the hop count by one for n_{opt} will carry on until the defined relay region size satisfies the condition that a certain number of candidate nodes can be found.

Thirdly, a relay region for the current hop will be defined according to the region calculated using the optimised hop count n_{opt} .

Finally, a relay node will be selected within the relay region to achieve energy efficiency.

5.3 Simulation Results

Table 5.2 shows the comparison of results of 15 simulation runs for the proposed EEE-GRP protocols with a low (3-4) hop count scenario. The results show the hop count, total transmission power of the selected route and total power consumption of the route which included the processing power of each relay node involved in routing. The processing power normally varies with different products. To simplify analysis, 30mW fixed processing power is assumed in the simulation. The EEE-GRP protocol proposed in this chapter shows the same hop count as that derived using the EE-GRP protocol. However, the total power consumption of the route for the EEE-GRP protocol proposed in this chapter is sometimes higher than the previous proposed EE-GRP protocol defined in Chapter 4. This is because the relay region for the first hop defined by enhanced protocol is smaller than the EE-GRP protocol which results in a lower number of candidate nodes and consequently higher power consumption for some routes. As observed from 15 simulation runs, the average ‘Total Tx Power’ and ‘Total Power Consumption’ of the EE-GRP protocol in Chapter 4 are 9.80mW and 107.80mW, while the corresponding figures for the improved protocol are 10.65mW and 108.65mW which are 8.67% and 0.79% higher respectively.

No. of Simulati on	EE-GRP			EEE-GRP		
	Hop Count	Total Tx Power (mW)	Total Power Consumption (mW)	Hop Count	Total Tx Power (mW)	Total Power Consumption (mW)
1	3	12.06	102.06	3	12.72	102.72
2	3	7.42	97.42	3	7.42	97.42
3	5	5.38	155.38	5	9.14	159.14
4	3	16.60	106.60	3	16.60	106.60
5	3	14.24	104.24	3	14.24	104.24
6	3	17.48	107.48	3	17.48	107.48
7	4	4.77	124.77	4	6.17	126.17
8	3	8.79	98.79	3	12.01	102.01
9	4	3.82	123.82	4	3.82	123.82
10	3	12.56	102.56	3	12.64	102.64
11	3	9.55	99.55	3	9.55	99.55
12	3	9.45	99.45	3	11.04	101.04
13	3	7.96	97.96	3	7.96	97.96
14	3	10.48	100.48	3	10.48	100.48
15	3	6.42	96.42	3	8.42	98.42
Average	3.27	9.80	107.80	3.27	10.65	108.65

Table 5.2. Simulation Results for Power Consumption with Low Hop-Count

Table 5.3 shows the simulation results for higher hop count scenarios. The improved EEE-GRP protocol performs much better than the previous EE-GRP protocol in terms of hop count. The average ‘Total Tx Power’ of the EE-GRP protocol is 5.88mW, while the corresponding value for the EEE-GRP protocol is 7.33mW which is 24.66% higher. The benefit of low hop count for the enhanced protocol is obvious when the processing power is taken into consideration for each relay node. The average total power consumption for the enhanced protocol is 161.33mW which is 20.87% lower than that of the EE-GRP protocol.

No. of Simulation	EE-GRP			EEE-GRP		
	Hop Count	Total Tx Power (mW)	Total Power Consumption (mW)	Hop Count	Total Tx Power (mW)	Total Power Consumption (mW)
1	7	6.89	216.89	6	8.23	188.23
2	6	6.42	186.42	5	6.59	156.59
3	7	4.33	214.33	5	10.22	160.22
4	5	6.08	156.08	5	6.08	156.08
5	6	3.66	183.66	5	7.29	157.29
6	8	5.07	245.07	5	6.34	156.34
7	7	4.94	214.94	5	6.25	156.25
8	6	5.23	185.23	5	7.74	157.74
9	6	7.75	187.75	5	4.04	154.04
10	6	3.52	183.52	5	3.86	153.86
11	7	4.90	214.90	5	5.30	155.30
12	6	8.90	188.90	5	4.79	154.79
13	8	4.65	244.65	6	13.45	193.45
14	7	4.87	214.87	5	3.67	153.67
15	7	11.04	221.04	5	16.12	166.12
Average	6.60	5.88	203.88	5.13	7.33	161.33

Table 5.3. Simulation Results for Power Consumption with High Hop-Count

Table 5.4 shows the comparison of route lifetime in a low hop-count scenario. In this scenario, the hop count of EEE-GRP route is not improved since only a maximum of 4 hops were simulated. EEE-GRP is not able to show its advantage in terms of hop count. While both protocols have the same hop count in the simulation, the enhanced protocol shows no increase for the route lifetime because it defined a limited size for each relay region which is smaller than the relay region size defined by EE-GRP hence a lower number of candidate nodes for each hop. The original EE-GRP protocol has an average

route lifetime of 23.41h and the corresponding figure for the EEE-GRP protocol is 21.07h.

No. of Simulati on	EE-GRP		EEE-GRP	
	Hop Count	Route Lifetime (hour)	Hop Count	Route Lifetime (hour)
1	3	16.23	3	16.23
2	3	20.93	3	20.93
3	4	68.65	4	51.80
4	3	19.48	3	19.48
5	3	15.48	3	15.48
6	3	16.71	3	16.71
7	3	21.05	3	21.05
8	3	9.08	3	9.08
9	3	46.73	3	30.04
10	3	43.67	3	43.67
11	3	17.16	3	15.48
12	3	16.54	3	16.54
13	3	9.50	3	9.50
14	3	19.96	3	19.96
15	3	10.03	3	10.03
Average	3.07	23.41	3.07	21.07

Table 5.4 Simulation Results for Route Lifetime with Low Hop-Count

Simulation comparison for the route lifetime with a high hop-count scenario is shown in Table 5.5. The improved protocol shows its advantage over the previous EE-GRP protocol in terms of hop-count. The average hop-count of EEE-GRP protocol is 6.13 while the EE-GRP protocol has an average hop-count of 7.47. However the route lifetime of enhanced protocol was lower than the EE-GRP protocol in this case due to the reduction of the hop-count which makes the size of relay region for each hop smaller and hence offers a smaller number of candidate nodes in the relay region. A higher power consumption of the link is normally observed when a relay node is selected from within a smaller number of candidate nodes when an optimised hop count is used to reduce the hop count.

No. of Simulati on	EE-GRP		EEE-GRP	
	Hop Count	Route Lifetime (hour)	Hop Coun	Route Lifetime (hour)
1	8	51.270113	6	50.839003
2	7	49.453564	6	46.8732
3	7	19.865215	6	18.577591
4	7	47.46603	6	42.524534
5	8	35.53968	6	18.986918
6	7	21.997753	6	19.004572
7	7	46.379041	6	37.698785
8	7	43.445248	6	21.576427
9	8	21.31395	6	20.755099
10	8	10.426106	6	7.887186
11	8	10.317595	6	3.875202
12	8	18.397442	7	14.361526
13	7	54.308309	6	33.103751
14	7	37.616751	7	18.680255
15	8	21.640423	6	19.098826
Average	7.47	32.63	6.13	24.92

Table 5.5 Simulation Results for Route Lifetime with High Hop-Count

5.4 Summary

This chapter introduced several modifications to an initial model aimed at providing an enhanced energy efficient geographic routing protocol. A hop-count optimization mechanism is developed to determine the optimized hop-count for the route instead of using the minimised hop-count.

The routing performance has been analysed in terms of power consumption and route life time to show the effects of the model revisions. The improved proposed EEE-GRP routing protocol is shown to provide lower hop-count over previous protocol while the energy efficiency is still maintained.

Chapter 6 Signalling Processes for Geographic Routing Protocol

6.1 Introduction

The new geographic routing protocol described in Chapters 4 and 5 requires an improvement of the signalling system for GRP. The signalling process gathers and distributes routing information between all nodes in the network. In this chapter, a signalling process for the new geographic routing protocol is described. The signalling system is simulated and the amount of signalling information is calculated and analysed.

6.2 Description of the Signalling Process

Figure 6.1 illustrates a flow chart of signal messages for mobile Ad-hoc networks (MANET) using the proposed geographic routing protocol as described in chapter 4 and 5. Each node will initially broadcast its geographic information to the whole network. On receipt of the flooding message, nodes can then provide a Geographic Table to maintain and update the location information of all the nodes in the network. Hello messages will be sent periodically to the neighbour nodes to help establish and update the neighbour table. A more detailed description of the process involved is now given.

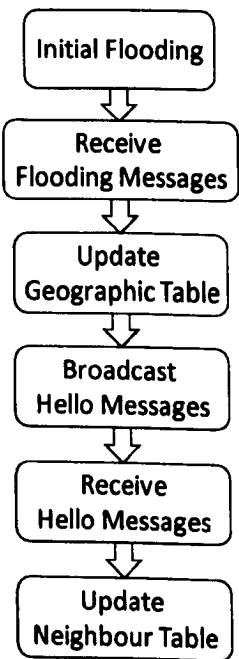


Figure 6.1 Flow Chart of Signal Messages

6.2.1 Initial flooding for co-ordinate distribution

The flooding mechanism performed in the initial stage by all nodes in the network allows the dissemination of co-ordinate information between all the nodes in the network. At the establishment of the network, an 'initial flooding' will be executed to bootstrap the network. It is assumed that each node can determine its own position using a GPS or related location service. In this procedure, each node broadcasts a beacon to the broadcast MAC address, containing only its own identifier (e.g., IP address) and position. Figure 6.2 shows the structure of the MAC address. The first three octets (in transmission order) identify the organization that issued the identifier and are known as the Organizationally Unique Identifier (OUI). The following three octets are assigned by that organization in nearly any manner they please, subject to the constraint of uniqueness. Packets sent to the broadcast MAC address are received by all stations on a local area network. In hexadecimal the broadcast address would be "FF:FF:FF:FF:FF:FF". A locally administered address is assigned to a device by a network administrator, overriding the burned-in address. Universally administered and locally administered addresses are distinguished by setting the second least significant bit of the most significant byte of the address.

As shown in Figure 6.2, if the least significant bit of the most significant byte is set to a 0, the packet is meant to reach only one receiving NIC. This is called unicast. If the least significant bit of the most significant byte is set to a 1, the packet is meant to be sent only once but still reach several NICs. This is called multicast. Instead of broadcasting to all the nodes in the network, the message can be sent to a certain group of nodes. Usually the network administrator determines which node is authorized to join the network [79]. Each authorized node has to manually set up the network parameters which are obtained from the network administrator.

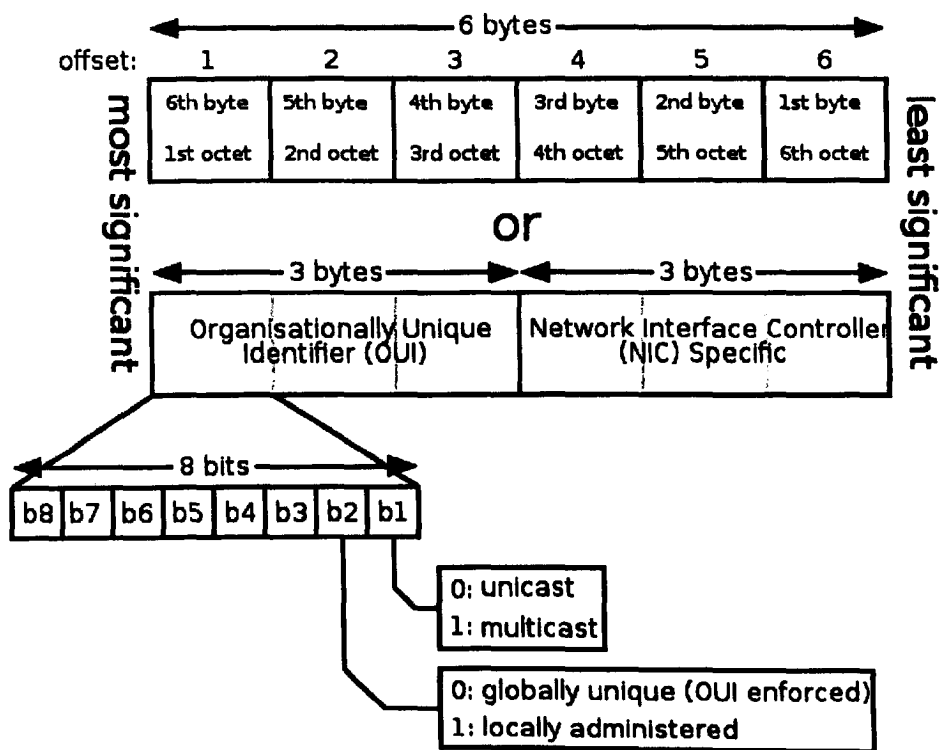


Figure 6.2 Structure of MAC Address

The position is encoded as two four-byte floating-point quantities, for x and y coordinate values. Some initial flooding messages may not be received by every node due to channel collision. The flooding signal may need to be re-transmitted to ensure the successful delivery to every node in the network. The number of initial floods sent out by each node then depends on the size and density of the network. The more nodes and the higher the density of the network, the large the number of initial flooding messages that need to be sent out to ensure all the nodes in the network know the information of each other. The content of a flooding message is as follows in Table 6.1. The size of each flooding message is 13 bytes.

Flooding Message		
Mes. Type	My ID (IP)	My Location
1 Byte	4 Bytes	8 Bytes

Table 6.1 Flooding Message

At the establishment of the network or when a node comes in and wants to join the network, an 'initial flooding' will be executed once or several times with a random time interval between transmissions to ensure that flooding message can be received by all

the nodes in the network. The retransmission of flooding message may be needed due to the nature of the wireless channel which may cause collisions as discussed previously. The number of re-transmissions of the flooding message is determined by the size and density of network, the number of nodes, the mobility of nodes and the network traffic load. Each node sends out its flooding message to its neighbour nodes and those nodes that successfully receive that flooding message will broadcast to their neighbour nodes as well. Multiple copies of the same flooding message may be received by some of the nodes, but only one copy will be re-broadcasted, others will be discarded. It was observed empirically that the flooding message needs to be sent three times to enable the flooding message to be received by every node in the network for simulated network scenarios.

A limited hop count can be applied to the flooding message in order to reduce the signalling overhead caused by short distance transmission. The hop count is then determined by the size of the network and the maximum transmission range of each node.

A time slot scheme for the flooding message may help to reduce the signalling overhead. Each node sends out its message at particular time slot to avoid collusion. But in mobile Ad-hoc networks, synchronization is a major challenge unless a centralized server is provided to support synchronization of all the nodes in the network.

6.2.2 Geographic Table

Instead of using a routing table, a geographic routing protocol uses a geographic table to store the location information of all the nodes in the network. When a node receives a flooding message from another node, it incorporates the data into its geographic table which takes the form shown in Table 6.2. The geographic table is updated when nodes that change position send out a new flooding message. This process will be discussed later.

Geographic Table		
ID	Location	Time Stamp
4 Bytes	8 Bytes	2 Bytes

Table 6.2 Geographic Table

6.2.3 Hello messages Broadcast

Hello messages are used to periodically provide all nodes with basic information about the neighbour nodes with which they have contact. Each node transmits a Hello message to the network broadcast address, containing only its own identifier (its IP address) and position. Through the Hello message process, each node determines the set of other nodes within direct communication range (within one hop). A simple Hello message structure as shown in Table 6.3 can be the same as the Flooding Message while the ‘mes. Type’ will distinguish the type of message. More information such as the position information of neighbour nodes can be provided to help routing determination. The time interval between Hello messages is normally determined by the following parameters:

The density of the nodes. The Hello messages from a node only affect its neighbour nodes. With a large network density, each node generally has more neighbour nodes. In this case, Hello messages will be sent out less frequently in order to reduce the interference.

The traffic load, when the traffic load increases, Hello message interval should become larger which means less Hello messages are sent out to reduce the signalling overhead and increase the network throughput.

The mobility of nodes. When a node moves away from its original position, it changes the connectivity with its neighbour nodes. Hence the Hello messages need to be sent out to inform its neighbour nodes. The faster the node moves, the more frequently Hello messages are sent out.

Hello Message		
Mes. Type	My ID	My Location
1 Byte	4 Bytes	8 Bytes

Table 6.3 Hello message

Hello Message			
Mes. Type	My ID	My Location	Battery Level
1 Byte	4 Bytes	8 Bytes	1 Byte

Table 6.4 Hello message with Battery Information

6.2.4 Neighbour Table Establishment

Any nodes which lies within the maximum transmission range of a source node and are able to receive packets from it successfully are the neighbour nodes of the source node. By receiving Hello messages from neighbour nodes, each node will establish a Neighbour Table as shown in Table 6.5.

Neighbour Table		
One-Hop Neighbours		
ID	Location	Validity Time
4 Bytes	8 Bytes	1 Byte

Table 6.5 Neighbour Table

Upon not receiving Hello message from a neighbour for a period longer than the validity time interval, a node assumes that the link to the neighbour is lost, and deletes the neighbour from its table. The IEEE 802.11 MAC layer also gives direct indications of link-level retransmission failures to neighbours which can be interpreted identically. To maintain local connectivity, Hello messages are periodically sent out to neighbour nodes.

6.2.5 Position Request

If the position information of the destination node is not included or valid in the neighbour table of the source node, a position request will be executed to help find the location of the destination. That request will be broadcasted through the network. Any nodes which contains the location information of the destination node will reply to the source node.

6.2.6 Flooding for Position updates

When a node moves, it can determine the distance it moves from its original location using GPS data. If the node has moved more than a predefined distance, then it will broadcast a co-ordinate message to the whole network to update its new position. The reason to define a distance threshold is to reduce the signalling overhead caused by co-ordinate messages. The distance threshold is defined based on the density and size of the networks and the mobility of nodes.

6.2.7 Forwarding

When a source node wants to communicate with a destination node, it firstly checks its neighbour table to see if the destination node is its neighbour. If so, it sends the packet to the destination directly. However, if the destination node is not its one-hop neighbour, a routing decision needs to be made to find a relay node within its neighbour table, which lies closer to the destination than the source node.

Geographic routing protocols usually follow a scheme based on the shortest distance to the destination. Each node that receives the data packet considers which of its neighbour nodes is closest to the destination and selects that neighbour to forward the packet to. To avoid loops, neighbour nodes that have already been traversed are omitted. Many such forwarding strategies have been proposed. Examples of which are discussed in chapters 2 and 4.

All those Geographic Forwarding schemes must meet the following basic requirements:

- Each node has a unique ID which is known to all the nodes throughout the network.
- Using GPS as an alternative positioning system, each node determines its location in the form of latitude and longitude.
- Each node periodically broadcasts a 'Hello' packet to its radio neighbours informing them of its ID, its current location and velocity.
- Each node maintains a local database containing its current neighbour IDs and geographic locations.

6.2.8 Face Routing

Greedy forwarding can lead into a dead end, where there is no neighbour closer to the destination. Then, face routing [80-83] helps to recover from that situation and find a path to another node, where greedy forwarding can be resumed. A recovery strategy such as face routing is necessary to ensure that a message can be delivered to the destination. The combination of greedy forwarding and face routing was first proposed in 1999 under the name GFG (Greedy-Face-Greedy) [84]. As shown in Figure 6.3 below a message is routed along the interior of the faces of the communication graph, with face changes at the edges crossing the S-D-line. The final routing path is shown in blue.

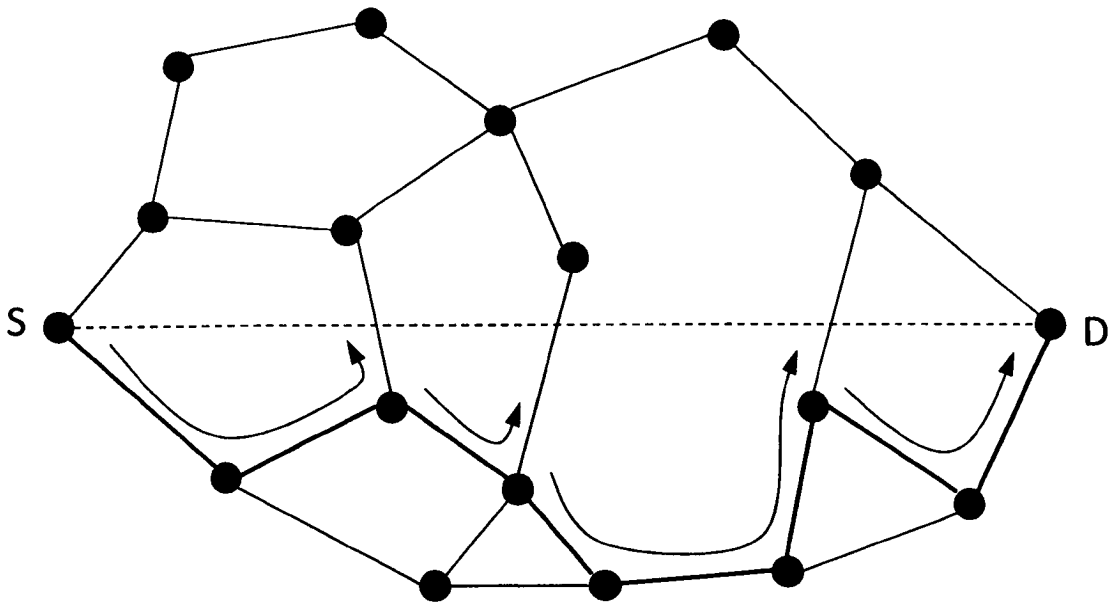


Figure 6.3 Example of Face Routing

6.3 Enhanced Signalling Messages

In conventional geographic routing protocols, a node will only send out its own location through Hello messages. However the signalling messages may require further neighbourhood information, which is reflected in the contents of messages sent by nodes when they, change activity status, react to topological changes, or simply periodically send update messages. A Hello message may contain, in addition to its own ID, its position and a list of one-hop neighbours. Other content is also possible, such as a list of one-hop neighbours with their positions and battery levels, a list of two-hop neighbours etc.

More detailed information for example a list of two (or more) hop neighbours can help to improve the routing efficiency as illustrated in Figure 6.4 below. In this example, node A and B are both candidate relay nodes for transmission of data for node S to node D. A protocol which simply identifies node position would select node A as the relay node since it is closer to destination node D than node B. However Node A may have no connection with D and to reach node D requires one more hop through node C. Node B may have direct connection with D and the route through node B will have one hop less than the route through node A. This route could only be chosen if the relevant neighbour data had first been communicated and established in the routing table of node S.

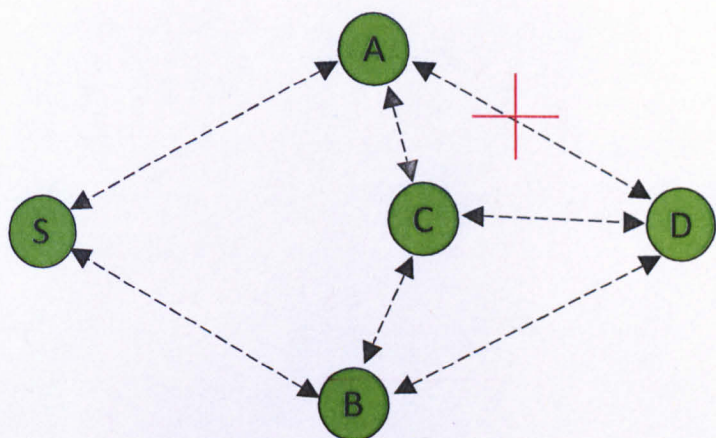


Figure 6.4 Final hop problem

An example of the neighbour table for node S is shown in Table 6.6. This table maintains and updates the location information of all nodes in the network.

Geographic Table		
ID	Location	Validity Time
A	(X_A, Y_A)	T_A
B	(X_B, Y_B)	T_B
C	(X_C, Y_C)	T_C
D	(X_D, Y_D)	T_D

Table 6.6 Neighbour Table for Node S

By receiving a simplified Hello messages as described in Table 6.3, nodes S establishes its routing table for node A and B as shown in Table 6.7. However, the routing information about node D is not included in the routing table which may cause the problem as discussed early.

Routing Table S				
One-Hop Neighbors				
ID	Location	Battery Level	Link Quality	Validity Time
A	(X_A, Y_A)	B_A	Q_A	T_A
B	(X_B, Y_B)	B_B	Q_B	T_B

Table 6.7 Improved Routing Table for Node S

In order to develop an energy efficient geographic routing protocol, other content is also possible in Hello message in addition to its own ID and position, such as a list of one-hop neighbours with their battery levels and positions. An example of an enhanced Hello message as shown below in Table 6.8 contains the battery information which can be used as one of the criteria for routing decision.

Hello Message			
Mes. Type	My ID	My Location	Battery Level
1 Byte	4 Bytes	8 Bytes	1 Byte
Neighbouring Table			
ID	Location	Battery Level	Link Quality
4 Bytes	8 Bytes	1 Byte	1 Byte

Table 6.8 Improved Hello message

The link quality is then estimated by measuring the power level of the received Hello message. The status of battery level and link quality can be updated through periodic Hello messages. An improved neighbour table which contains the link quality for one hop neighbours is shown in Table 6.9.

Neighbour Table				
One-Hop Neighbours				
ID	Location	Battery Level	Link Quality	Validity Time
4 Bytes	8 Bytes	1 Byte	1 Byte	1 Byte

Table 6.9 Improved Neighbour Table I

In order to select the proper route to node D, routing information about two-hop neighbours is needed as shown in Table 6.10.

Neighbour Table					
One-Hop Neighbours					
ID	Location	Battery Level	Link Quality	Validity Time	
4 Bytes	8 Bytes	1 Byte	1 Byte	1 Byte	
Two-Hop Neighbours					
ID	Location	Battery Level	Link Quality	Intermediate node	Validity Time
4 Bytes	8 Bytes	1 Byte	1 Byte	4 Bytes	1 Byte

Table 6.10 Improved Neighbour Table II

By using enhanced Hello message, node A and B send out more information which includes its neighbouring table as shown in Table 6.11 and 6.12.

Hello MessageA			
Mes. Type	My ID	My Location	Battery Level
Hello	A	(X_A, Y_A)	B_A
Neighbouring Table			
ID	Location	Battery Level	Link Quality
C	(X_C, Y_C)	B_C	Q_C
S	(X_S, Y_S)	B_S	Q_S

Table 6.11 Hello message for Node A

As shown in Table 6.11 for the Hello message from node A, only node C and S are in the neighbouring table since the node D has no direct connection with node A.

Hello MessageB			
Mes. Type	My ID	My Location	Battery Level
Hello	B	(X_B, Y_B)	B_B
Neighbouring Table			
ID	Location	Battery Level	Link Quality
C	(X_C, Y_C)	B_C	Q_C
S	(X_S, Y_S)	B_S	Q_S
D	(X_D, Y_D)	B_D	Q_D

Table 6.12 Hello message for Node B

From the Hello message from node B as shown in Table 6.12, routing information for node D can be found which will help node S to select route to node D. The final neighbour table for node S is shown in Table 6.13, from which node S can find the route to D with a minimised hop count.

Neighbour Table S					
One-Hop Neighbors					
ID	Location	Battery Level	Link Quality	Validity Time	
A	(X _A , Y _A)	B _A	Q _A	T _A	
B	(X _B , Y _B)	B _B	Q _B	T _B	
Two-Hop Neighbors					
ID	Location	Battery Level	Link Quality	Intermediate node	Validity Time
C	(X _C , Y _C)	B _C	Q _C	A	T _C
D	(X _D , Y _D)	B _D	Q _D	B	T _D

Table 6.13 Neighbour Table of Node S

By utilizing the enhanced signalling messages, all the nodes are able to obtain full detailed routing information for their two-hop neighbours which will help facilitate a routing decision. An example for a network with 11 nodes is shown in Figure 6.5 below.

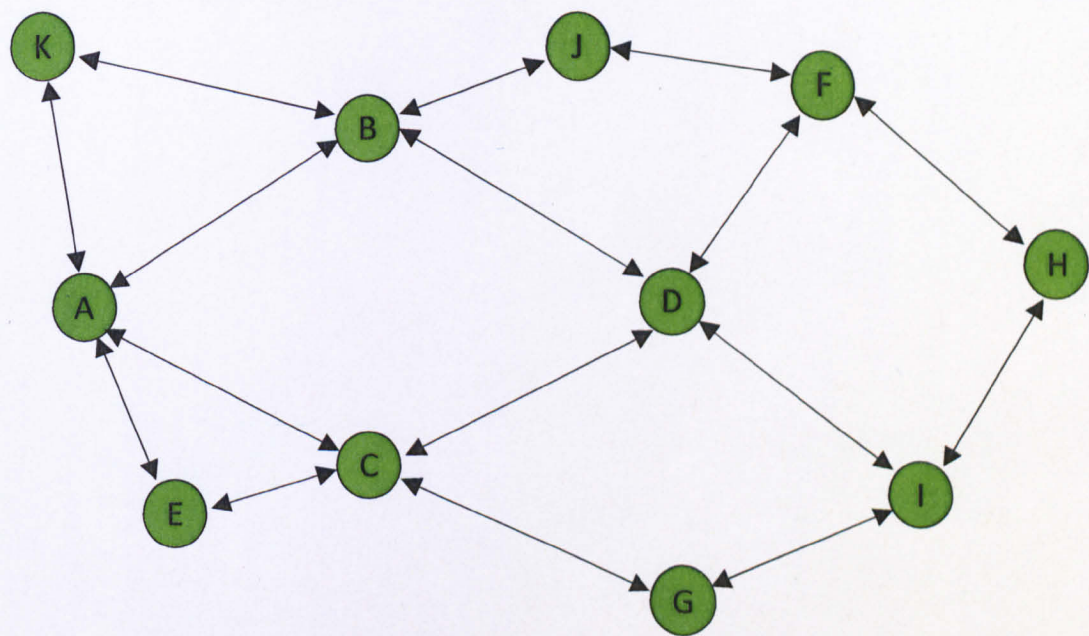


Figure 6.5 Network Scenario with 11 Nodes

The black arrow lines show the connectivity of the nodes. Hello messages are periodically sent out by each node which contain the information of the node itself and its neighbours. At the beginning of the network, the Hello message may only contain the information of the node itself because no information from its neighbours has been received yet and such information can be updated later. Tables 6.14 to 6.16 show the

final version of Hello messages of node A, D and H respectively with full neighbour information.

Hello Message A			
Mes. Type	My ID	My Location	Battery Level
Hello	A	(X_A, Y_A)	B_A
Neighbouring Table			
ID	Location	Battery Level	Link Quality
B	(X_B, Y_B)	B_B	Q_B
C	(X_C, Y_C)	B_C	Q_C
E	(X_E, Y_E)	B_E	Q_E
K	(X_K, Y_K)	B_K	Q_K

Table 6.14 Hello message of Node A

Hello Message D			
Mes. Type	My ID	My Location	Battery Level
Hello	D	(X_D, Y_D)	B_D
Neighbouring Table			
ID	Location	Battery Level	Link Quality
B	(X_B, Y_B)	B_B	Q_B
C	(X_C, Y_C)	B_C	Q_C
F	(X_F, Y_F)	B_F	Q_F
I	(X_I, Y_I)	B_I	Q_I

Table 6.15 Hello message of Node D

Hello Message H			
Mes. Type	My ID	My Location	Battery Level
Hello	H	(X_H, Y_H)	B_H
Neighbouring Table			
ID	Location	Battery Level	Link Quality
F	(X_F, Y_F)	B_F	Q_F
I	(X_I, Y_I)	B_I	Q_I

Table 6.16 Hello message of Node H

By receiving Hello messages from its neighbours, a node updates its neighbour table for routing purposes. The neighbouring table information from received Hello messages is then classified into 'One-Hop Neighbours' and 'Two-Hop Neighbours' and is stored in the neighbour table. Such a neighbour table is kept updated by obtaining the latest

information from periodic Hello message mechanism. Tables 6.17 to 6.19 show the Neighbour tables of node A, H and D respectively.

Neighbour Table A					
One-Hop Neighbours					
ID	Location	Battery Level	Link Quality	Validity Time	
B	(X _B , Y _B)	B _B	Q _B	T _B	
C	(X _C , Y _C)	B _C	Q _C	T _C	
E	(X _E , Y _E)	B _E	Q _E	T _E	
K	(X _K , Y _K)	B _K	Q _K	T _k	
Two-Hop Neighbours					
ID	Location	Battery Level	Link Quality	Relay Node	Validity Time
D	(X _D , Y _D)	B _D	Q _D	C	T _D
G	(X _G , Y _G)	B _G	Q _G	C	T _G
J	(X _J , Y _J)	B _J	Q _J	B	T _J

Table 6.17 Neighbour Table of Node A

Neighbour Table H					
One-Hop Neighbours					
ID	Location	Battery Level	Link Quality	Validity Time	
F	(X _F , Y _F)	B _F	Q _F	T _F	
I	(X _I , Y _I)	B _I	Q _I	T _I	
Two-Hop Neighbours					
ID	Location	Battery Level	Link Quality	Relay Node	Validity Time
D	(X _D , Y _D)	B _D	Q _D	I	T _D
G	(X _G , Y _G)	B _G	Q _G	I	T _G
J	(X _J , Y _J)	B _J	Q _J	F	T _J

Table 6.18 Neighbour Table of Node H

Neighbour Table D					
One-Hop Neighbours					
ID	Location	Battery Level	Link Quality	Validity Time	
B	(X_B, Y_B)	B_B	Q_B	T_B	
C	(X_C, Y_C)	B_C	Q_C	T_C	
F	(X_F, Y_F)	B_F	Q_F	T_F	
I	(X_I, Y_I)	B_I	Q_I	T_I	
Two-Hop Neighbours					
ID	Location	Battery Level	Link Quality	Relay Node	Validity Time
A	(X_A, Y_A)	B_A	Q_A	B	T_A
E	(X_E, Y_E)	B_E	Q_E	C	T_E
G	(X_G, Y_G)	B_G	Q_G	I	T_G
H	(X_H, Y_H)	B_H	Q_H	I	T_H
J	(X_J, Y_J)	B_J	Q_J	F	T_J
K	(X_K, Y_K)	B_K	Q_K	B	T_K

Table 6.19 Neighbour Table of Node D

With the enhanced signalling message scheme, full detailed routing information for all the nodes in the network can be established as shown in Table 6.19 for the neighbour table of node D.

6.4 Simulation & Results Analysis

6.4.1 Simulation Scenario

Five routing protocols namely Ad-hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR), Optimized Link State Routing (OLSR), Geographic Routing Protocol (GRP) and the Enhanced Energy Efficient Geographic Routing Protocol (EEE-GRP) are simulated and compared in this session to show their performance in terms of routing signalling overhead by looking at the amount of routing traffic overhead generated and the transmission delay.

The EEE-GRP is developed by using an improved Hello message type as shown in Table 6.20 which contains the location information of neighbour nodes to assist routing

decision. After receiving the improved Hello message from neighbours, each node establishes a routing table for its one-hop and two-hop neighbours.

Hello Message			
Mes. Type	My ID	My Location	Battery Level
1 Byte	4 Bytes	8 Bytes	1 Byte
Neighbouring Table			
ID	Location		Battery Level
4 Bytes	8 Bytes		1 Byte

Table 6.20 Improved Hello message

6.4.2 Signalling Processes for other Routing Protocols

In this section, the major signalling processes for AODV, DSR and OLSR protocols are introduced. A comparison of simulation results follows this section.

6.4.2.1 Signalling Processes for AODV

Route discovery

The AODV [26] model implements the complete set of route discovery mechanisms: broadcasting route requests (RREQ), creating a reverse path while forwarding RREQ, route replies (RREP) by intermediate nodes or destination node, and creating a forward path while forwarding RREP. Rate limit, maximum number of retries, and exponential backoff between each retry during the route discovery are also implemented.

Maintaining sequence numbers

The AODV model maintains sequence numbers to avoid loops during route formation or update. Each node maintains a sequence number that is updated accordingly while receiving AODV control packets.

Hello messages

A node offers link connectivity information by broadcasting local Hello messages. Only the nodes that are part of an active route use Hello message. Every HELLO_INTERVAL seconds, each node checks whether it has sent a broadcast within the last HELLO_INTERVAL seconds. If not, it broadcasts a Hello message.

Maintaining local connectivity

Each forwarding node maintains its continued connectivity to its active next hops. If a node doesn't receive any packet (Hello or otherwise) from a neighbour within

$\text{ALLOWED_HELLO_LOSS} \times \text{HELLO_INTERVAL}$ seconds, it assumes that the link to the neighbour is lost. The following protocols also have the same parameter for the Hello message process.

Route maintenance

Each AODV routing table entry is associated with a route expiry timer. This timer is calculated during the route discovery process. The timer is refreshed with each packet using that route entry. If a route is not used for more than ACTIVE_ROUTE_TIME seconds, it is marked **INVALID** and cannot be used for forwarding packets. An active route can also be marked **INVALID** after detecting a link break (next hop connection failure). A route is deleted from the routing table only DELETE_PERIOD seconds after it has been marked invalid.

Route reply by intermediate node

During route discovery, an intermediate node having a "fresh enough" route to the destination can send a reply to the source. This feature can be switched off by enabling the **DESTINATION ONLY** flag. With this flag set, only the destination node can reply to a route request.

Gratuitous route reply

In order for a destination to learn of routes to the originating node, the originating node sets a "gratuitous route reply" (G) flag in the route request. If an intermediate node replies to a route request having the G flag set, it also unicasts a gratuitous route reply to the destination node.

Expanding ring search

To prevent unnecessary network-wide dissemination of route requests, originating nodes use the expanding ring search technique. In this technique, the originating node initially uses a TTL equal to TTL_START in the route request IP header and sets the timeout for receiving a route reply to $\text{RING_TRAVERSAL_TIME}$ seconds. In case of timeout without a route reply, the originator broadcasts the request again with TTL incremented by TTL_INCREMENT . This continues until TTL reaches TTL_THRESHOLD , beyond which TTL is set to NET_DIAMETER (network-wide broadcast) for each attempt. There is a limit on the maximum number of attempts,

determined by the Route Request Retries attribute, as set in the Route Discovery Parameters.

Local repair

When a link break occurs in an active route, the node upstream of the break can attempt to repair the link locally if local repair is enabled on that node. During the local recovery, the node buffers the currently undeliverable packet and starts a route discovery for the destination node. Local repair attempts are often invisible to the originating node.

6.4.2.2 Signalling Processes for DSR

Route Discovery [27]

The DSR model implements the complete set of route discovery mechanisms comprising of broadcasting route requests to find a route and receiving route replies with a specific route to the destination.

Route Maintenance

As DSR is designed for mobile networks, route maintenance is done to verify whether the next hop along the source route is reachable. The complete set of route maintenance mechanisms comprising of sending acknowledgement requests and receiving acknowledgements is implemented.

Route Cache

Each node maintains a route cache comprising of routing information in the network. The route cache is implemented as a "path cache" where the node maintains a set of paths to each destination. The node chooses the route with the least number of hops to the destination.

Replying to Route Requests using Cached Routes

A node can reply to a route request for which it is not the destination, by searching its own route cache for a route to the destination of the route request.

Non-propagating route request

DSR implements a "non-propagating" route request mechanism where the route request is broadcast only to the immediate neighbours of the node performing route discovery. This request is not re-broadcasted by the neighbours. If one of the neighbours is the

destination or has a route to the destination of the request, it would send a reply. If the node performing route discovery does not receive a reply within a certain period, it times out and sends out a "propagating" route request which is broadcasted to the entire network.

Packet Salvaging

When an intermediate node forwarding a packet detects that the next hop for the packet is broken, if the node has an alternative route to the destination of the packet, the node "salvages" the packet by sending it along this alternative route

Automatic Route Shortening

The route used by a packet may be automatically shortened if one or more of the intermediate nodes in the route become no longer necessary. This may happen when a node operating in promiscuous mode receives a packet in which it is not the next hop, but is named in the unexpended portion of the route. The node can then remove the nodes that are no longer needed before itself in the source route.

6.4.2.3 Signalling Processes for OLSR

MPR flooding mechanism [40]

The OLSR model implements the MPR (Multi Point Relay) flooding mechanism to broadcast and flood Topology Control (TC) messages in the network. The algorithm is implemented as suggested in OLSR RFC 3626. This mechanism takes advantage of controlled flooding by allowing only selected nodes (MPR nodes) to flood the TC message. Each node selects an MPR to reach its two-hop neighbours.

Neighbour sensing mechanism

The OLSR model implements the neighbour sensing mechanism through periodic broadcast of Hello messages. These Hello messages are one-hop broadcasts (never forwarded) that carry neighbour type and neighbour quality information. The neighbour sensing mechanism provides information on up to two-hop neighbours. Generation and processing of the Hello messages are implemented as suggested in the OLSR RFC.

Topology discovery/diffusion mechanism

Periodic and triggered Topology Control (TC) messages implement the topology discovery/diffusion mechanism in the OLSR model. TC messages are generated by MPR nodes and carry information about MPR selector nodes. These messages are

diffused throughout the network using controlled flooding, thus helping to form a topology for each node with its reachable nodes and previous hop information.

OLSR maintains several tables to store the link, neighbour, two-hop neighbour, and topology information. All table entries are associated with an expiry time. Some of the entries implement an active timer (scheduling an interrupt) and some use the lazy method (not scheduling a specific interrupt with each entry) to remove the old information.

6.4.3 Simulation for the routing protocols

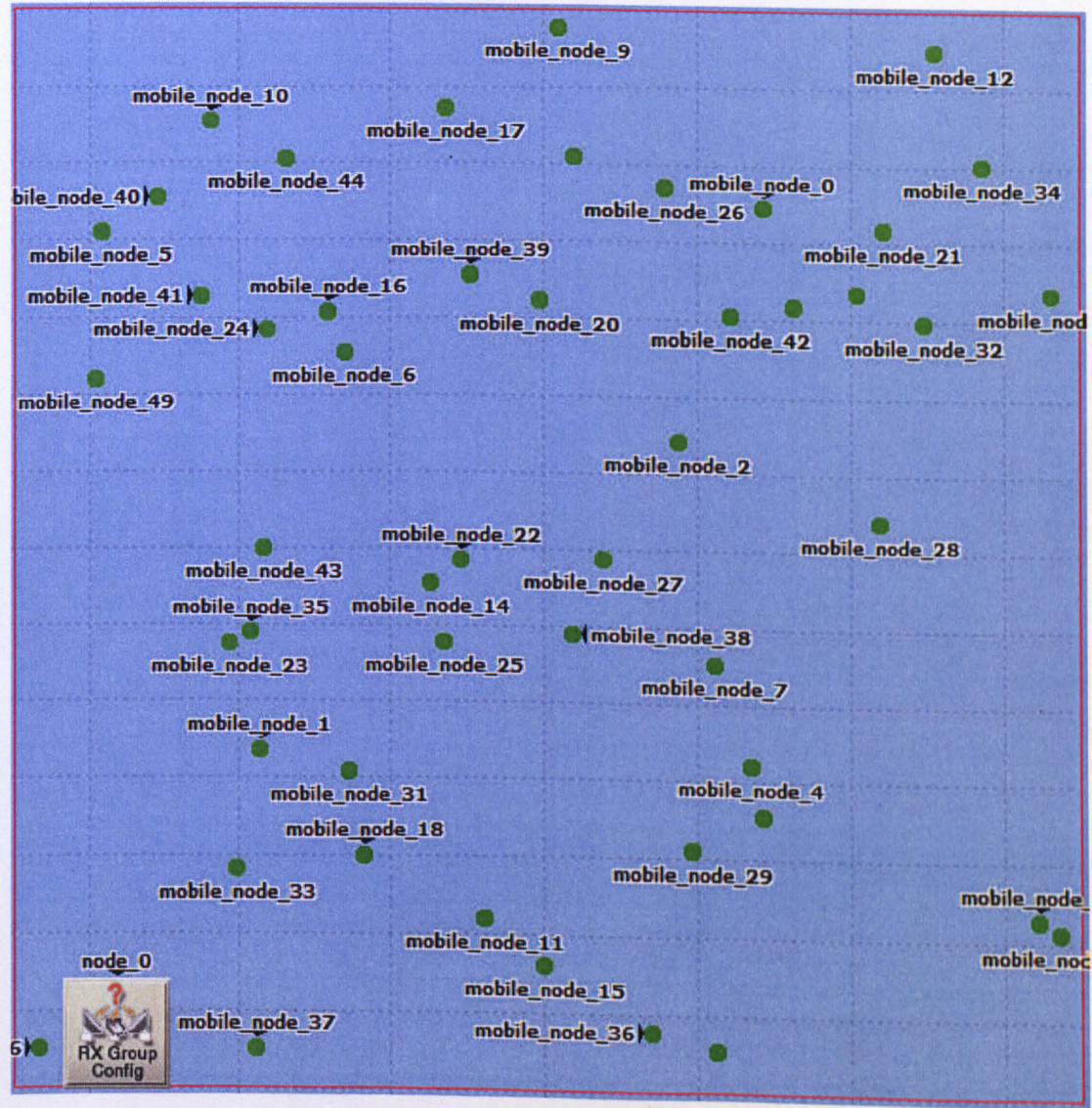


Figure 6.6 Simulation Scenario

Figure 6.6. shows the simulation scenario contains 50 nodes randomly deployed in a 350X350m² network. The Free Space Path Loss (FSPL) model was used in the

simulation to represent the path loss. The transmission power is 0dBm (1mW) for all the nodes and the receiver sensitivity is -95dBm. Packets with a power less than this threshold are not sensed and decoded by the receiver. Hence, such packets are not detected by the receiver through its physical sensing mechanism. The packets whose received power is higher than this threshold are considered as valid packets. They are sensed by the MAC and are recorded as being received successfully unless the BER due to interference, background noise and/or collision with other valid packets is higher than a specified threshold. The maximum transmission range was 150m for each node and all the nodes are static although the power settings in this simulation enable a valid transmission distances in excess of 500 meters between transceivers. Any nodes separated more than 150m will not be able to communicate directly with each other even if the path loss is below the threshold. This function is achieved by using the ‘The Dynamic Receiver Group configuration’ object within OPNET as shown in Figure 6.7. This function computes receiver groups, which are the set of possible receivers with which a node can communicate. This configuration object specifies:

- the criteria (channel match, distance threshold, and pathloss threshold) used to determine which receivers belong to a receiver group
- when the groups are used
- how often group membership is computed

By restricting the set of possible receivers, the number of transmissions sent out by the nodes in the network can be reduced as well as the simulation runtimes. The decrease in simulation speed depends on the following factors:

- Number of possible neighbours for each node with respect to the total number of receivers
- Number of re-computations during the simulation (refresh interval)

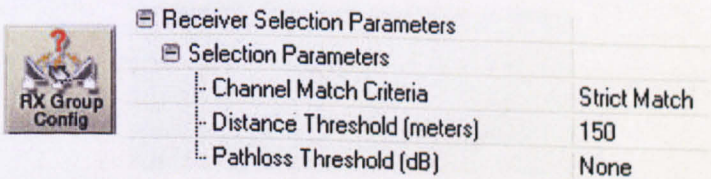


Figure 6.7 MANET RX Group Config

By setting up the maximum transmission range in the simulation, multi-hop routes with no more than three hops were observed in the following simulations.

In order for the OPNET software to calculate signalling bits as packet rate, it is necessary for the source and destination nodes to be assigned and data packets to be generated as traffic between these nodes. The MANET traffic generator as discussed in chapter 3 is used to generate various data rates. The packet inter-arrival time specified as uniform(2.0, 2.5) generates packets at the source node every 2 to 2.5 seconds with a step size of 10^{-6} s. The probability density function for a uniform distribution on the interval $[a, b]$ is

$$P(x) = \begin{cases} 0 & \text{for } x < a \\ \frac{1}{b-a} & \text{for } a \leq x \leq b \\ 0 & \text{for } x > b \end{cases} \quad (6.1)$$

The actual parameters used for the traffic generation in this simulation are as follows.

Hello message interval: each node broadcasts a Hello message to all its neighbours every hello interval seconds. In the simulation, all the nodes will send out a Hello message after every Hello message interval. A constant value for the hello interval would result in a large number of collisions between the Hello message protocols. It is therefore appropriate to establish a degree of probability in hello packet generation. To avoid synchronization of neighbours' Hello messages, as observed by Floyd and Jacobson [85], each message's transmission is jittered by using the uniform distribution function based on a defined Hello message interval. The transmission delay for a Hello message of 13bytes for the GRP protocol at 11Mbps data rate is $9.45\mu\text{s}$ and theoretically a maximum number of 105769 Hello messages can be sent out each second. In this simulation, 50 Hello messages are generated every second by 50 nodes in the network which need a minimum time of $482\mu\text{s}$. The parameter uniform (0.9, 1.0) is therefore used for the Hello message interval to generate random values between 0.900000 and 1.000000 to provide sufficient different transmission times for each Hello message to ensure the collision probability is significantly low to avoid the need for multiple hello packet transmissions.

As stated earlier, the packet inter-arrival time is used for generating random outcomes for times between successive message packet generation. The packet inter-arrival time is defined in order to simulate the route request for reactive routing protocols such as AODV and DSR. In those protocols, a routing decision needs to be made for each generated data packet which requires the routing information to be regularly updated. A

timely update for the network topology and link connectivity is therefore needed through the periodic Hello message exchange. With high mobility of the nodes, Hello messages are required to be sent out more frequently in order to provide instant routing information, however in this simulation all nodes are static. A uniform (1.0, 1.5) is initially used for the packet inter-arrival time based on the previous hello interval setting which is uniform (0.9, 1.0). The uniform (0.5, 1.0) and uniform (0.25, 0.5) are also used to simulate an increase in the packet generation rate which subsequently affects the signalling overhead of the network.

The following data parameters are also used in the simulation:

- **Packet Message size (bits):** a constant 1024 bits is used for the packet size [86, 87].
- **Neighbour Expiry Time (seconds):** constant 2s. If a Hello message is not received from a neighbour node within the neighbour expiry time, which is 2 seconds in this simulation, the node is not considered a neighbour anymore.
- **Number of Initial Floods:** 3 times. Flooding messages may get lost due to channel collisions and the routing information carried within that message would then not be obtained by all the nodes in the work. For example, in a GRP network all nodes exchange position information with each other through the flooding messages. If the source node is not aware of the position of the destination node, a position request message needs to be sent out in order to update that information. Through initial testing, it was shown that information convergence could be established using a maximum of three initial floodings, after which all the nodes were able to share information with every node. Following this flooding, no position request message was sent out.
- **Physical Data rate:** 11Mbps. A lower data rate could be used but this may result in collisions occurring due to the longer transmission time when sending packets. This would degrade the network performance.
- **The source and destination of each transmission** are selected randomly.

By using the parameters above for the traffic generation, the transmission delay for a data packet of 1024bits at 11Mbps data rate is $931\mu\text{s}$ which means the maximum number of packets which can be sent out within a one second period is 10742.

6.4.3.1 Discussion of the signalling process for on demand and proactive routing protocols

AODV and DSR are both on demand protocols in which route information is discovered only as needed. The route is normally determined by route latency and a route with the shortest time (lowest latency) will be selected.

In the DSR protocol, the entire path to the destination is supplied by the source in a packet header that utilizes an extension header following the standard IP header [27]. Route discovery is undertaken when a source needs a route to a destination. The source node broadcasts a Route Request message for the specified destination. Each intermediate node adds itself to the path in the message and forwards (broadcasts) the message towards the destination. The destination node unicasts the Route Reply message which contains the complete path built by intermediate nodes to the source. Intermediate nodes cache overheard routes to reduce the need for route discovery. A Route Reply may be returned to the source by the intermediate node if it already has a path stored. In a single query-reply cycle, the source node learns a route to each intermediate node in the route in addition to the destination node. Each intermediate node also learns the route to other nodes on the route. Promiscuous listening also helps nodes to learn the route to every node on the route.

For the AODV protocol [26], the route discovery procedure is undertaken whenever a node needs a “next hop” to forward a packet to the destination. The source node then broadcasts a Route Request (RREQ) message for the specified destination. The intermediate node forwards (broadcasts) the message toward the destination and creates a next-hop entry for the reverse path to the source, to use when sending a reply. After the destination node receives the message, it unicasts a Route Reply (RREP) message to the source which contains the sequence number and hop-count field. Each intermediate node creates a next-hop entry for the destination as the RREP is received identified as a forward along “reverse path” hop. There is no source routing or promiscuous listening for AODV, as such AODV relies on a route discovery flood more often than the DSR protocol, and so generates more signalling overhead than DSR which benefits from cached overhead routes stored in intermediate nodes.

Being a proactive protocol, OLSR inherits the stability of a link state algorithm and has the advantage of having routes available immediately when required due to its proactive

nature [40]. OLSR is optimized over the classical link state protocol and is tailored for mobile Ad-hoc networks. It discovers and maintains the routes to all destinations within the network so the routing information is immediately available when required. The protocol uses Hello and Topology Control (TC) messages to discover and then disseminate link state information throughout the mobile ad-hoc networks. Individual nodes use this topology information to compute the next hop destinations for all nodes in the network, using shortest hop forwarding paths. Topology information is exchanged with other nodes of the network regularly. Each node selects a set of its neighbour nodes as "multipoint relays" (MPR). In OLSR, only nodes, selected as such MPRs, are responsible for forwarding control traffic, intended for diffusion into the entire network. OLSR minimizes the overhead from flooding of control traffic by using MPRs to retransmit signalling messages. This technique significantly reduces the total number of retransmissions required to flood a signalling message to all nodes in the network.

As a proactive routing protocol, geographic routing has the advantage of low signalling overhead when compared with other routing protocols. This is shown in the results presented in this section which examines the signalling overhead for some different protocols. The protocols considered are the Optimized Link State Routing Protocol (OLSR) based on Link State Routing (LSR), Ad-hoc On-Demand Distance Vector Routing (AODV), Dynamic Source Routing protocol (DSR), Geographic Routing protocol.

The basic concepts of OLSR, AODV and DSR were discussed in details in early chapters, but are summarised here to aid the discussion. In Link State Routing, each node periodically floods the status of its links and rebroadcasts link state information received from its neighbours. Every node keeps track of link state information received from other nodes. This information is then used by each node to determine the next hop to each destination.

A general characteristic comparison of those routing protocols is shown in Table 6.21.

Characteristic	DSR	AODV	OLSR	GRP
Routing Philosophy	Reactive	Reactive	Proactive	Proactive
Type of Routing	Source routing	Hop-by-hop routing	Hop-by-hop routing	Hop-by-hop routing
Frequency of Updates	As needed	As needed	Periodically	Periodically
Worst case	Full flooding	Full flooding	Pure link state	Full flooding
Multiple routes	Yes	No	No	No

Table 6.21 Comparison of Mobile Ad-hoc Routing Protocols

6.4.4 Simulation Results Analysis

A series of signalling rates for 5 routing protocols (ADOV, DSR, OLSR, GRP and EEE-GRP) were obtained through simulation. The results were compared and analysed in the following sections.

6.4.4.1. Traffic Source Packet Inter-arrival time: uniform (1.0, 1.5)

As shown in the Figure 6.8 below, AODV has the highest signalling rate. Although AODV and DSR are both reactive routing protocols, DSR has much lower routing traffic overhead than AODV and has access to greater amount of routing information than AODV. As indicated in the previous section, DSR uses routing cache aggressively, and maintains multiple routes per destination. DSR uses route replies to all requests reaching and determining a route to a destination from a single request cycle. The source node learns many alternative routes to the destination, which is useful when the primary route fails. This saves the overhead of a new discovery flood which would otherwise be required. With the packet inter-arrival time equal to uniform(1.0, 1.5), DSR achieved the lowest signalling overhead, even lower than the proactive routing protocols.

AODV uses one route per destination. It maintains at most one entry per destination in the routing table. The destination node only replies once to the request arriving first and ignores the rest.

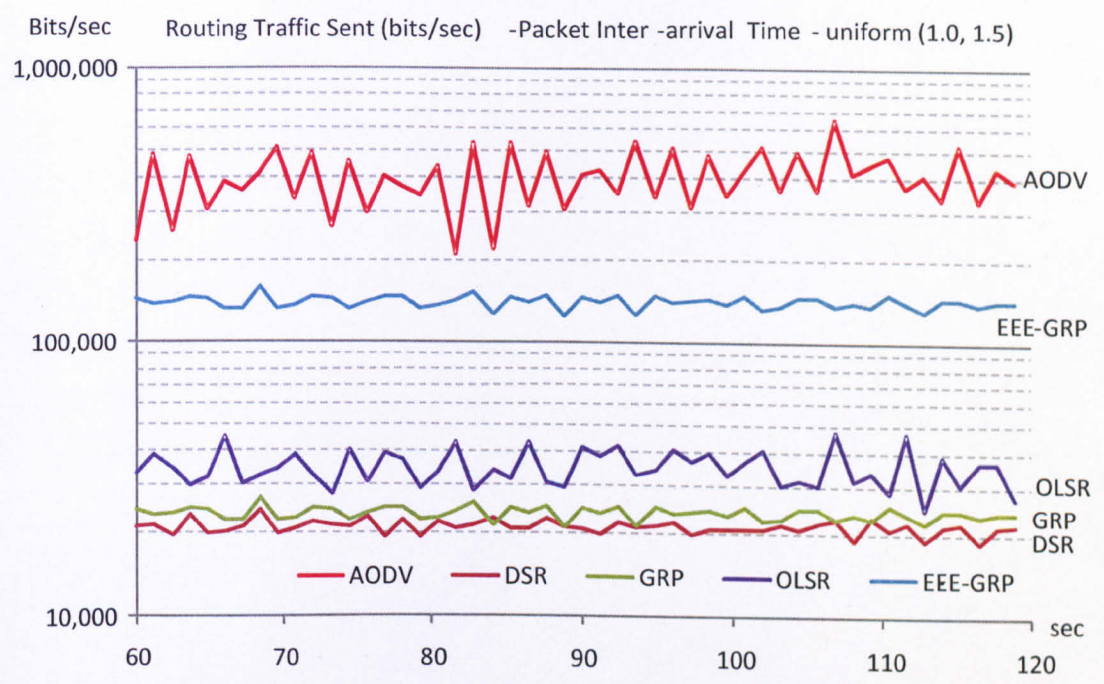


Figure 6.8 Comparison of Signalling Traffic (bits/sec) for Different Routing Protocols

The GRP protocol achieved the second lowest signalling overhead of all the routing protocols. There are 50 nodes in the network and each node generates a Hello message following the uniform (0.9, 1) distribution. The size of Hello message after IP encapsulation is 55 bytes for this protocol as shown in Figure 6.9 below.

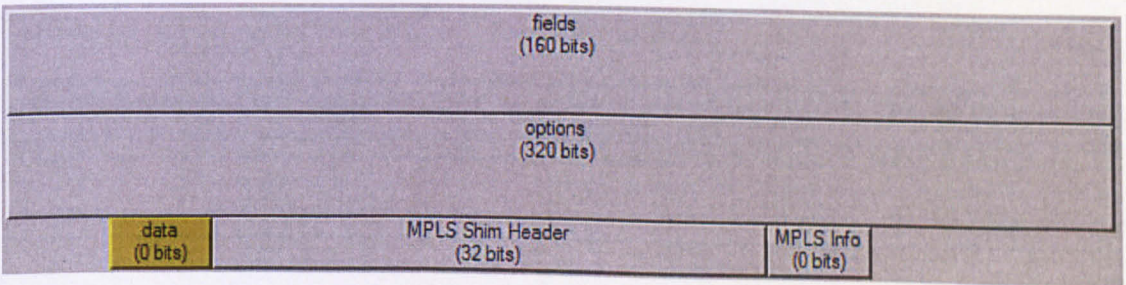


Figure 6.9 Packet Format for IP_dgram_V4

Therefore the signalling overhead for GRP can be calculated using the formula below:

$$\text{Maximum Rate: } 50 * (1/0.9) * 55 * 8 = 24444 \text{ bits/s} \tag{6.2}$$

$$\text{Minimum Rate: } 50 * 1 * 55 * 8 = 22000 \text{ bits/s} \tag{6.3}$$

Where the maximum rate for the GRP signalling overhead is obtained when the Hello message interval is equal to 0.9s and the minimum rate is obtained when the Hello message interval is equal to 1s. The average rate is then calculated below:

$$\text{Average Rate: } (24444+22000)/2 = 23222 \text{ bits/s} \tag{6.4}$$

The EEE-GRP protocol which is developed based on GRP has much higher signalling overhead than GRP due to the larger size of the Hello message. The enhanced Hello message contains the neighbour information as described previously. Each neighbour node will add 13 bytes into the size of the Hello message for its location information. Below in Table 6.22 shows the number of neighbour nodes that are contained in the Hello messages for EEE-GRP routing protocol in this simulation with the transmission range of 150m for all the nodes.

Cumulative Total Number of Neighbour Nodes in the Hello message	1070
Extra Hello message Size for All the Nodes (Bytes)	13910
Average Number of Neighbour Nodes for Each Node	21
Average Extra Hello message Size for Each Node (Bytes)	278

Table 6.22 Number of Neighbour Node for Hello messages

The simulation collected the number of neighbours for each node within 150m transmission range and determined the Hello message size based on that. The cumulative total number of neighbour nodes in the Hello messages for all the nodes is then obtained by summing of the number of neighbours for all the nodes. The extra Hello messages size for all the nodes is obtained by using the total size of Hello messages for all the nodes deducting the total size of simple Hello messages which is 55 bytes for each node. Since there are 50 nodes in the network, the average number of neighbour nodes for each node and the average extra Hello message size for each node were then obtained by the total number divided by 50 nodes.

Therefore the signalling overhead for EEE-GRP can be calculated using the formula below:

$$\text{Maximum Rate: } (50 * 55 + 13910) * 8 * (1/0.9) = 148089 \text{ bits/s} \tag{6.5}$$

$$\text{Minimum Rate: } (50 * 55 + 13910) * 8 * 1 = 133280 \text{ bits/s} \tag{6.6}$$

Where the maximum rate for the EEE-GRP signalling overhead is obtained when the Hello message interval is equal to 0.9s and the minimum rate is obtained when the Hello message interval is equal to 1s. The average rate is then calculated below:

$$\text{Average Rate: } (148089+133280)/2 = 140685 \text{ bits/s} \quad (6.7)$$

The results for average signalling overhead sent by the five established routing protocols (AODV, DSR, OLSR, GRP, EEE-GRP) with a packet inter-arrival time uniform(1.0, 1.5), are shown below in Figure 6.10. The average rates for signalling overhead were obtained by dividing the total routing traffic sent during the simulation time by the simulation time. AODV leads to a typical average signalling packet rate of 400kbit/s. This relatively high signalling rate arises from the continuous flooding of the route request messages through the network. AODV relies on a route discovery flood more often than other routing protocols, and so generates more signalling overhead. As we can see from the results, the average rates for GRP and EEE-GRP routing protocols is slightly different from the theoretical results above, this is due to the uniform distribution function used for Hello message generation which means the Hello messages are not sent out constantly and variable rates are applied.

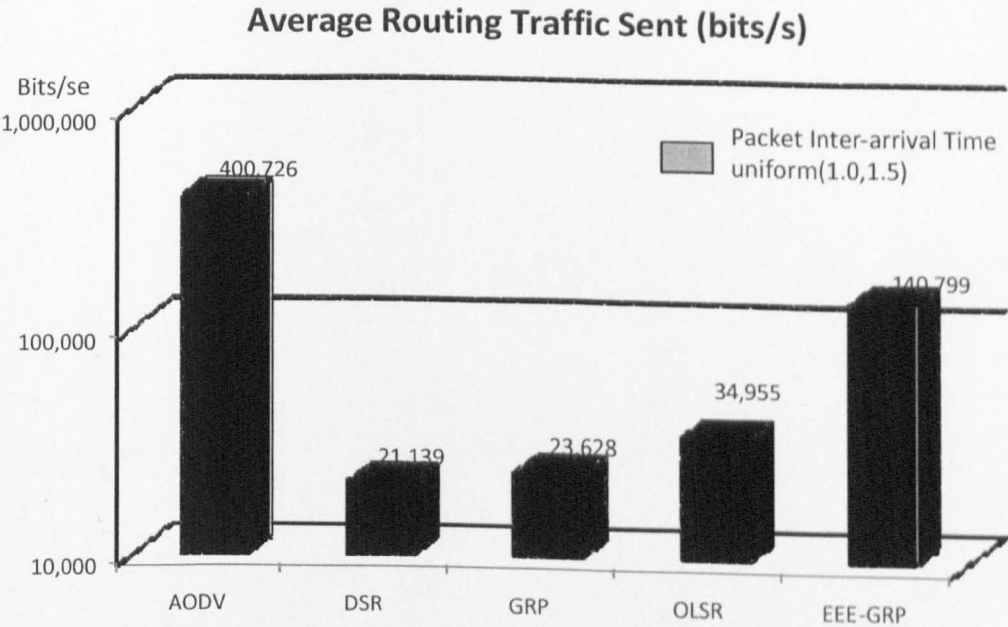


Figure 6.10 Comparison for Average Signalling Overhead Sent (bits/sec)

The difference between GRP and EEE-GRP arises from the simplified Hello messages used by GRP compared with the enhanced Hello message type used by EEE-GRP which contains more detailed information that can be used as one of the criteria for

routing decisions in addition to its own ID and position. In this simulation, the average routing traffic sent by EEE-GRP is 140,799bits/s while GRP has 23,628bits/s of that.

There are certain criteria which affect the Hello message size within the EEE-GRP protocol such as the maximum transmission range of each node, the density of the network and path loss model used in the network.

To examine the effects of increased routing traffic on the signalling overhead, the packet inter-arrival time is reduced and results for these changes are presented below.

6.4.4.2. Traffic Source Packet Inter-arrival time: uniform (0.5, 1.0)

Figure 6.11 below shows the results for routing traffic with a uniform (0.5, 1.0) for the Traffic Source Packet Inter-arrival Time which increases the packet generation rate. Being proactive routing protocols, with a higher packet generation rate, AODV and DSR generate higher signalling overhead.. The result for GRP, EEE-GRP and OLSR remains almost the same as shown in the previous results. This arise because the total signalling messages sent out for GRP, EEE-GRP and OLSR are only affected by the Hello message intervals not the packet generation rate. Since the Hello message intervals were the same as used in previous simulation, the results for GRP, EEE-GRP and OLSR also remain nearly the same. GRP achieved a lower signalling overhead than the other routing protocols.

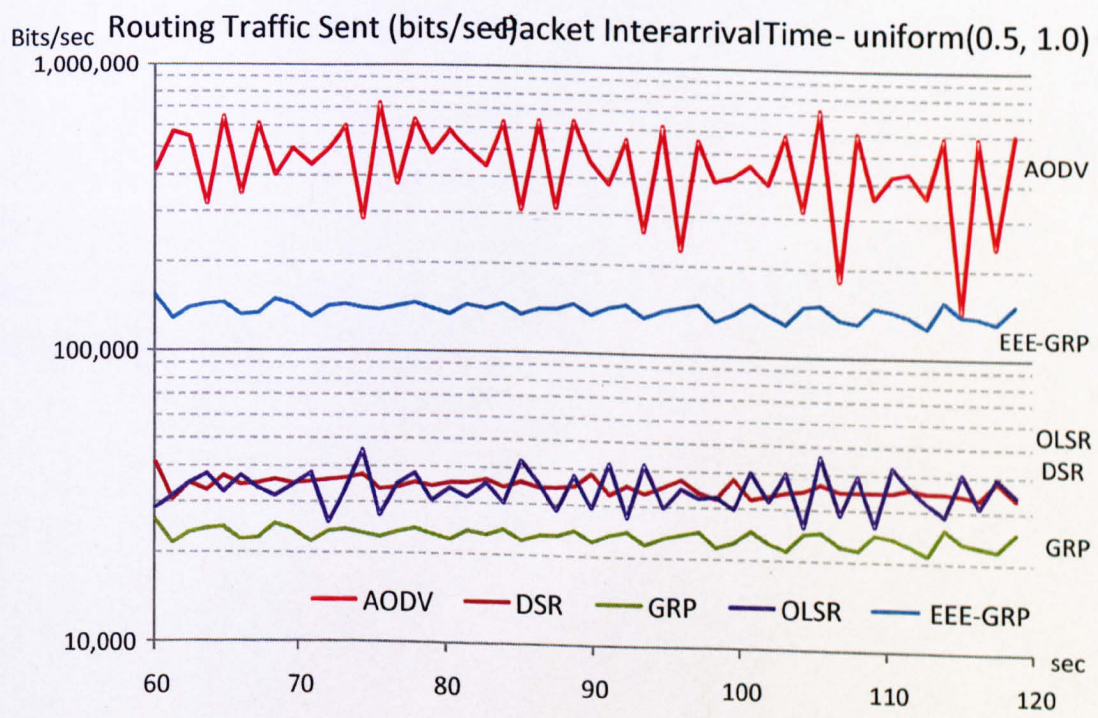


Figure 6.11 Comparison of Signalling Overhead Sent (bits/sec)

The results for the average signalling overhead sent for all the routing protocols at packet inter-arrival time uniform(0.5, 1.0) are shown below in Figure 6.12. As we can see from the results, GRP, EEE-GRP and OLSR retained a similar signalling rate to the previous simulation whereas the other two reactive routing protocols had higher signalling rates.

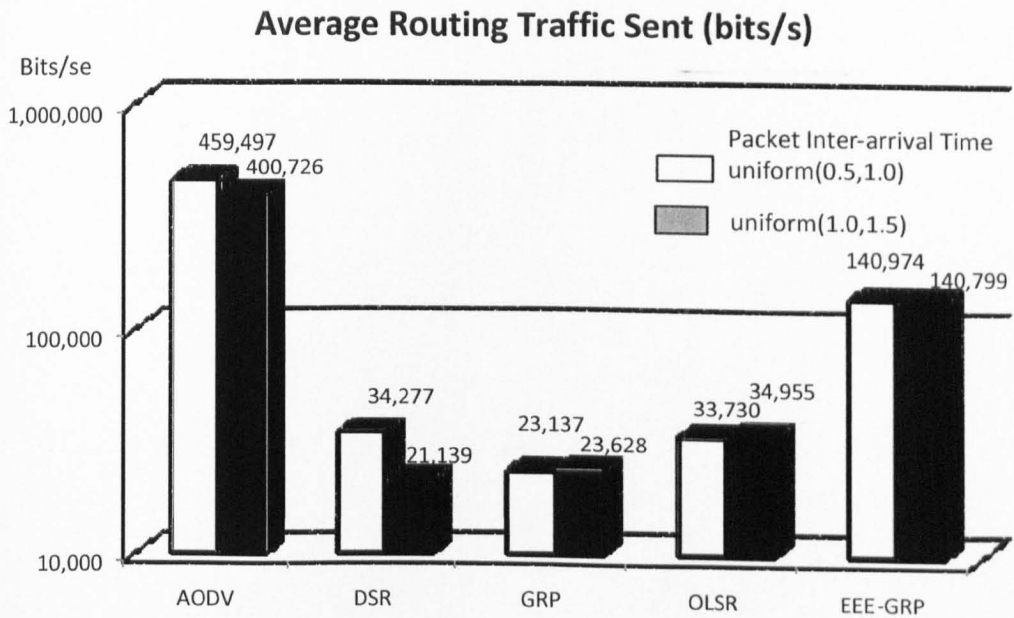


Figure 6.12 Comparison for Average Signalling overhead Sent (bits/sec) II

6.4.4.3. Traffic Source Packet Inter-arrival time: uniform (0.25, 0.5)

The signalling rates for Traffic Source Packet Inter-arrival Time with uniform (0.25, 0.5) which increases the packet generation rate are shown in Figure 6.13. As expected, the AODV still had the highest signalling rate. The signalling overhead for DSR increased with the increase in the packet generation rate. As proactive routing protocols, GRP, EEE-GRP and OLSR maintained similar results as before with the same Hello message rates used for the earlier simulations.

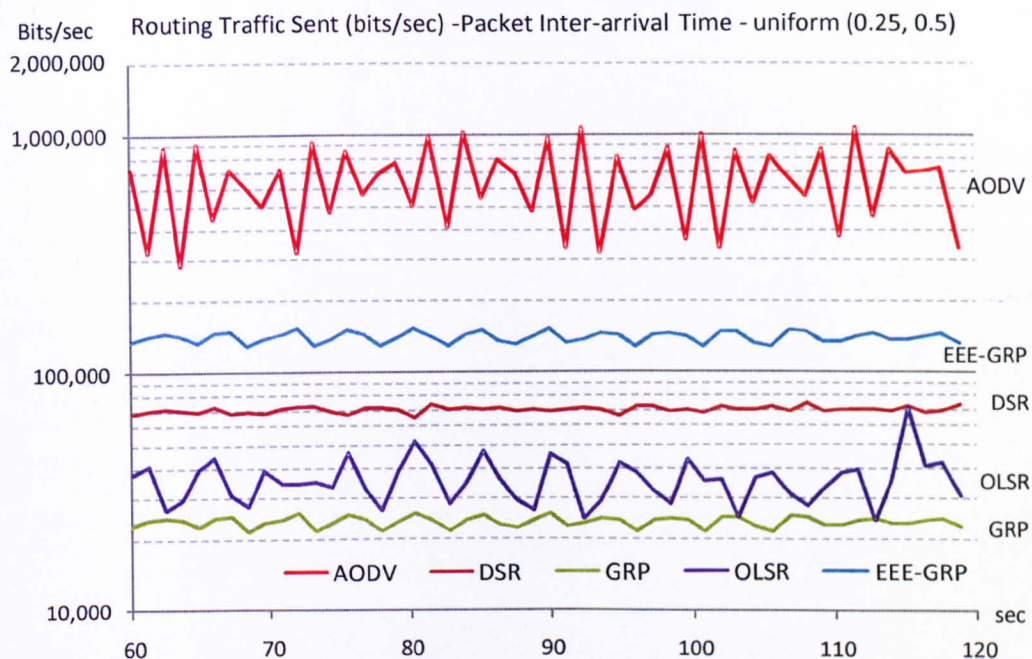


Figure 6.13 Comparison for Signalling overhead Sent (bits/sec)

The comparison for average routing traffic sent by all the routing protocols considered is shown below in Figure 6.14. The signalling overhead for DSR was the lowest when packet inter-arrival time is uniform (1.0, 1.5). However, when a higher packet generation rate was used, the signalling overhead for DSR increased and exceeded that of GRP and OLSR. For the packet inter-arrival time with uniform(1.0, 1.5), the average data rate can be obtained by using the following equation.

$$1024 \times 50 \times 1 / ((1.0 + 1.5) / 2) = 40,960 \text{ bit/sec} \quad (6.8)$$

Where the average packet rate is $1 / ((1.0 + 1.5) / 2)$, each packet is 1024bits and there are 50 nodes in the network, hence the average rate is 40,960 bits/sec at packet inter-arrival time with uniform(1.0, 1.5).

As the packet inter-arrival time reduces from uniform(1.0, 1.5) to uniform(0.25, 0.5), more data packets are generated. The data rate increases from 40,960bits/sec to 136,533bits/sec.

It can be seen that the routing signalling overhead for the AODV and DSR increases rapidly with the increase of the packet inter-arrival whereas the signalling overhead in GRP, EEE-GRP and OLSR changes little as shown in Figure 6.16. This is expected because of its nature of the reactive protocols used in AODV and DSR. Large overhead

is expected as more data packets are generated with reduced packet inter-arrival time resulting in increasing route discovery signalling.

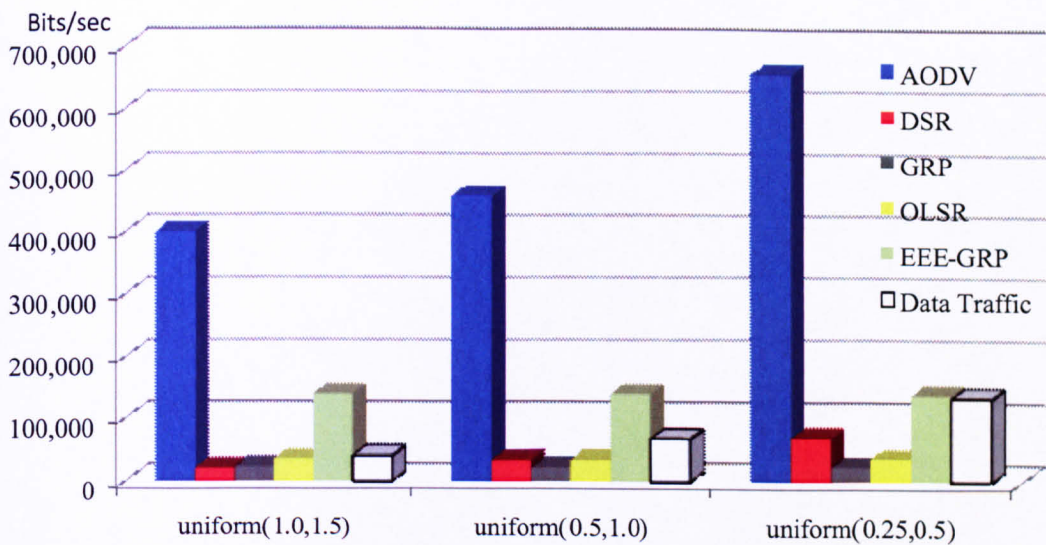


Figure 6.14 Comparison for Average Signalling Overhead Sent (bits/sec)

Though both AODV and DSR are reactive protocols, the routing overhead of AODV is much greater than that of DSR due to following reasons [88-91]. AODV is a timer based scheme which updates its cache irrespective of the route being valid or stale, if that route is not used for a certain period of time which is 3 seconds in this simulation. After this period, a route which is not used and refreshed will be marked as invalid and then be removed from the routing table. However, if a network is highly dynamic, a small value for this attribute is preferred to remove stale routes quickly. DSR is not timer based and it will update its route information in the cache on detection of a link breakage. AODV maintains only the next hop per destination. DSR maintains multiple routes per destination. DSR gathers more information whereas AODV has limited access to information and finally the overhead is high in AODV due to the absence of promiscuous listening. As DSR adopts this feature it can save multiple routes in its cache, which results in a low generation of overhead.

6.4.4.4 Effects of variation of transmission range on signalling overhead for the EEE-GRP protocol

As with the analysis done chapters 4 and 5 it is instructive to consider the effects of varying the transmission range on the average signalling overhead sent by EEE-GRP and results for this analysis are presented in this section.

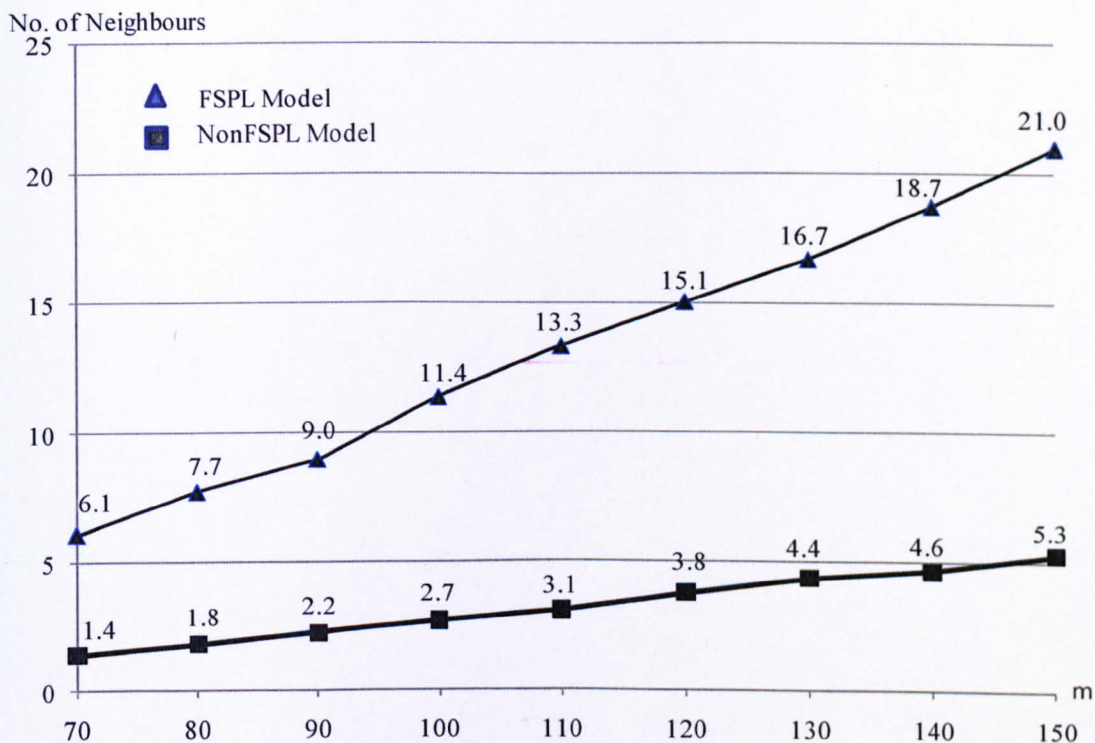


Figure 6.15 Average Number of Neighbour per Node for EEE-GRP

Figure 6.15 above shows the average number of neighbours per node under different transmission range from 70 to 150m. With the decrease of transmission range, the average number of neighbour per node is also reduced. With a FSPL model, the average number of neighbours per node was 21 with transmission range of 150m while this figure dropped to 6.1 when the transmission range reduced to 70m. The reduction of the average number of neighbours per node didn't follow a square law as the coverage of each node does. This is because the nodes which lie near the boundary of the network have fewer neighbour nodes than the nodes which lie in the centre of the network. When a Non-FSPL model is used, the average number of neighbours per node was 5.3 with a transmission range of 150m which is 75% lower than that with FSPL model. This figure was down to 1.4 with a transmission range of 70m and some nodes have no neighbours in this case.

The average signalling overhead sent by EEE-GRP under different transmission range from 70 to 150m is shown below in Figure 6.16. The size of Hello message for EEE-GRP is reduced when the transmission range decreases. The lower average signalling rates can be observed with smaller transmission range. When the transmission range reduced from 150m to 70m, the average signalling rate drops by 59.1% from 141kbit/s to 58kbit/s with FSPL model. With NonFSPL model, the average signalling rate at

150m transmission range is 51kbit/s which is only 35.9% of found in with the FSPL model. The average signalling rate drops by 41.2% from 51kbit/s at 150m range to 30kbit/s at 70m range. As we can see from the results, the network performance under a smaller transmission range can achieve a much lower signalling rate. However, with the reduction of the transmission range, the number of neighbours of each node decreases which can limit or even prevent a route being found. During the simulation under an even smaller transmission range than 70m, some nodes were observed that had no neighbours within their coverage range and those nodes were isolated from the network. The hop count between the source and destination nodes also increases. The power consumption of the selected route is higher with a higher hop count, therefore, more relay nodes may be required and higher total energy consumption may be observed. An optimised transmission range may be discovered to provide the balance between hop count and energy consumption and this aim is studied in the later section.

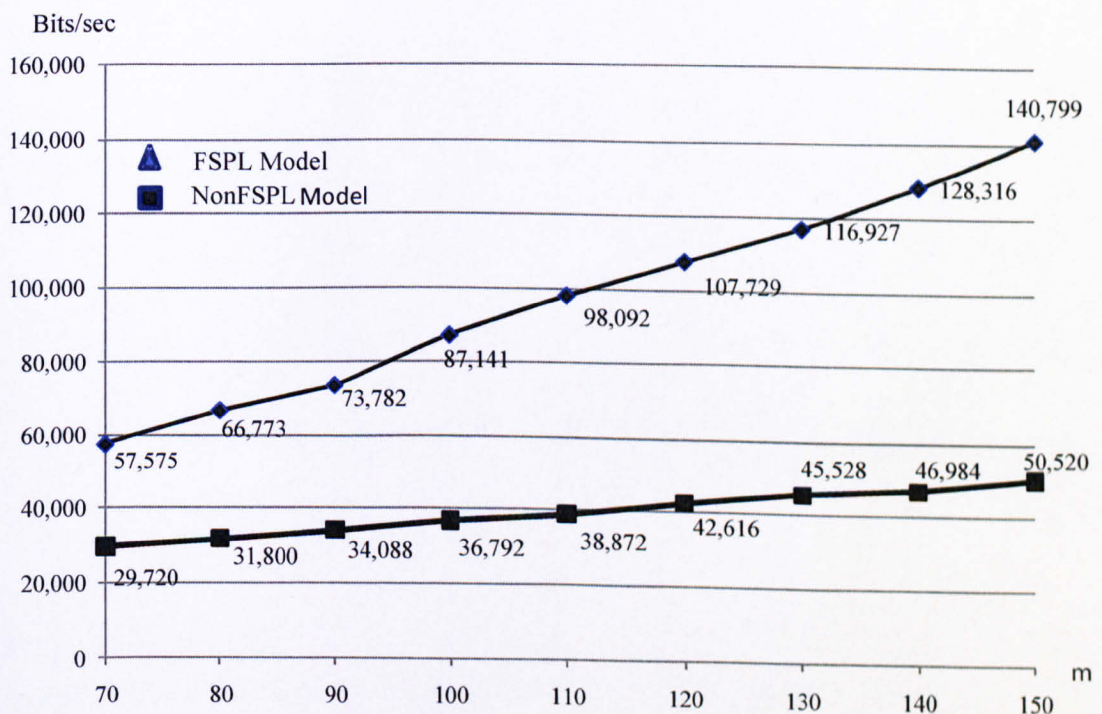


Figure 6.16 Comparison of Average Signalling Overhead Sent by EEE-GRP

6.4.4.5. Simulation Results with Various Traffic Patterns

In this section, different values for the traffic generation parameters have been used and simulated to study the performance of EEE-GRP for a 50-node network. Different data rates for the data traffic with different packet sizes and packet inter-arrival time were

simulated and analysed. In Figure 6.17, different packet sizes were used from 1k to 12k bits while the packet inter-arrival time remained uniform(1.0, 1.5). Results showed that all the routing protocols maintained similar results for the signalling overhead under different packet sizes. As reactive routing protocols, AODV and DSR send out routing traffic for each generated data packet the signalling overhead for AODV and DSR is determined by the number of packets generated rather than the size of the packet. However if the packet size becomes too large there would be an increased probability of collision during transmission of the large packets. Packets which are larger than the maximum allowed data size need to go through a fragmentation process to split into several smaller packets. Proactive routing protocols like OLSR, GRP and EEE-GRP send out routing messages periodically independently of the data traffic. So that their signalling overhead remains similar under different packet sizes.

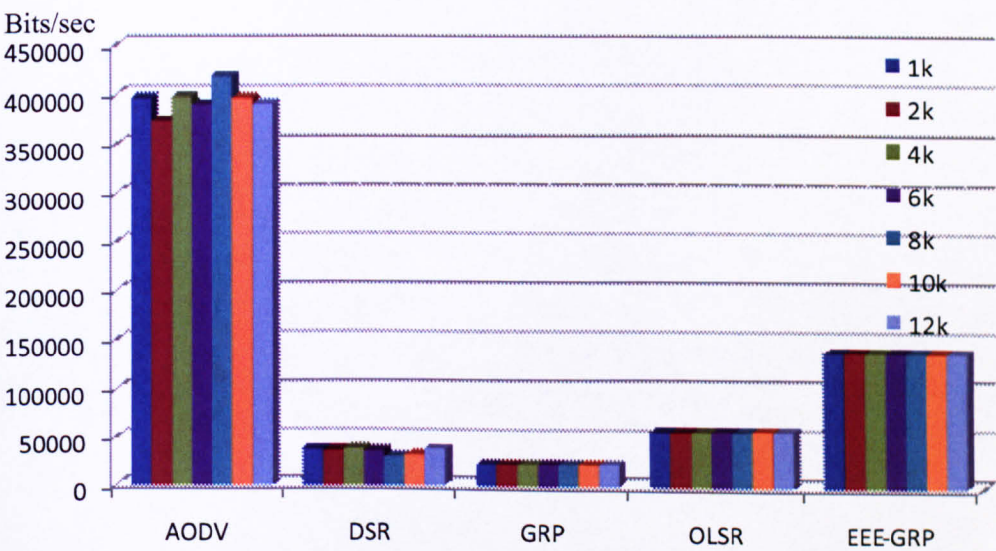


Figure 6.17 Comparison of Average Signalling Overhead Sent with Different Packet Size

To examine the effect of higher packet generation rate rather than the use of larger packets, Figure 6.18 shows the results for signalling overhead with different packet inter-arrival time while the packet size remained a constant 1024 bits. The packet inter-arrival time changed from uniform(1.0, 1.1), uniform(0.75, 0.85), uniform(0.5, 0.6) to uniform(0.25, 0.35) and more packets were generated accordingly. As reactive routing protocols, AODV and DSR send out more signalling overhead when more data packets are generated as can be seen by the increasing trend shown in Figure 6.20. For example, an inter-arrival time of uniform(0.25, 0.35) generated 1.58 times more packets/sec than uniform(1.0, 1.1) for AODV and 2.57 times for DSR.

OLSR, GRP and EEE-GRP send out signalling messages periodically and as a consequence the signalling overhead is little affected by increasing the packet inter-arrival time.

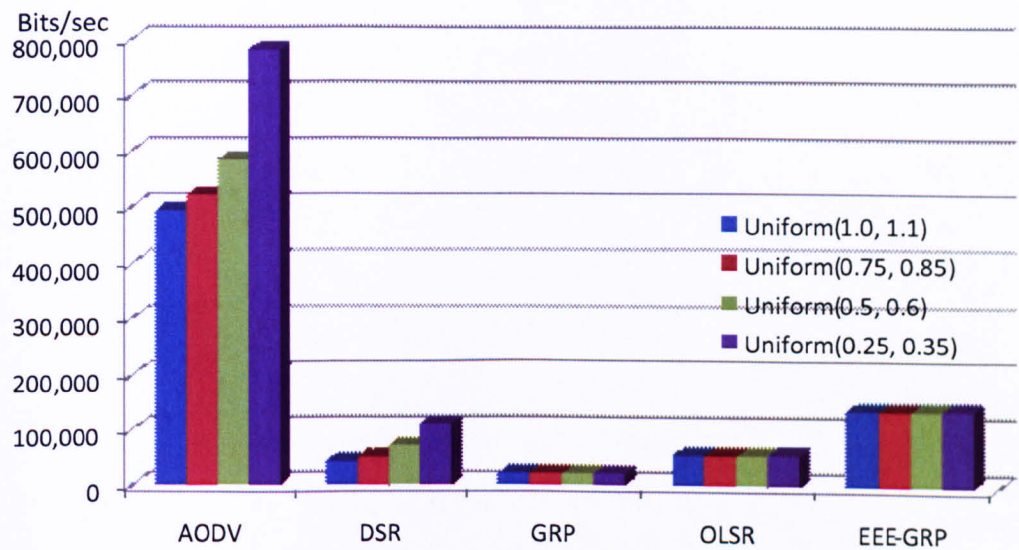


Figure 6.18 Comparison of Average Signalling Overhead Sent with Different Packet Inter-arrival Time

6.4.4.5. Simulation Results with Different Node Density and Path Loss Models

In order to further evaluate the performance of EEE-GRP, a series of simulation results were collected under different node densities. The physical size of the network remains the same as $350 \times 350 \text{m}^2$. The total number of nodes in the analysis varies from 25, 50, 100 to 150. The same routing parameters as in the previous simulation were used. The packet inter-arrival time follows uniform(1.0, 1.5) and the maximum transmission range was 150m. A realistic non free space path loss model as described in earlier chapters was also used to compare with the results obtained with FSPL model.

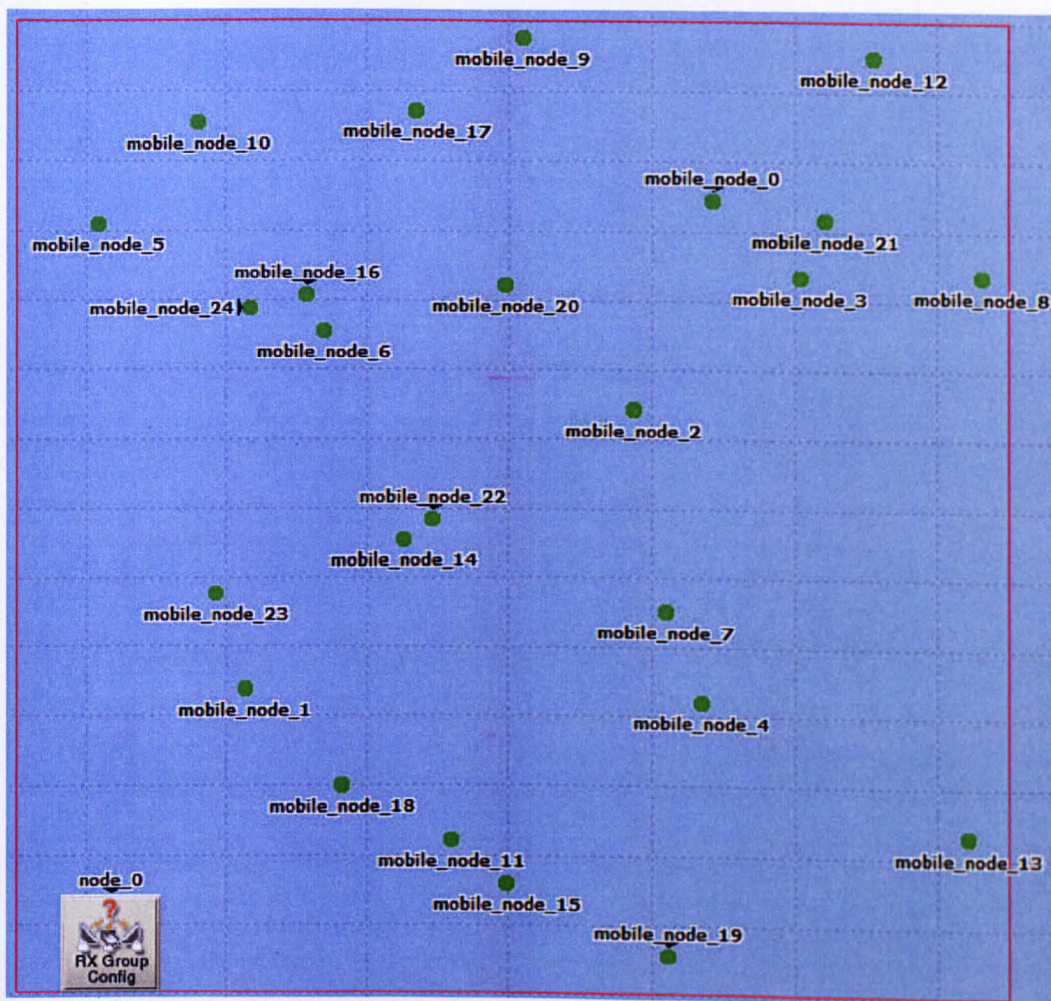


Figure 6.19 Simulation Scenario with 25 Nodes

Figure 6.19 shows a network with 25 randomly deployed nodes. The results with FSPL and NonFSPL model are shown in Figure 6.20 and 6.21 respectively. For all protocols in the NonFSPL scenario, each node has fewer neighbour nodes than in the FSPL scenario which influences the signalling overhead observed.

The GRP protocol still gives the lowest signalling overhead in both scenarios and the while the overhead for AODV changed little and remained the highest. The routing traffic sent out by DSR increased when the path loss changed from FSPL to NonFSPL because the number of neighbour nodes was reduced in the NonFSPL scenario which means DSR obtained less routing information from neighbours when compared with FPSL scenario. As a result more signalling messages had to be sent out by DSR to obtain the relevant routing information.

The signalling overhead for OLSR also slightly increased due to reduced number of neighbour nodes within the transmission range in the NonFSPL scenario. More MPRs were selected in this case which generated more signalling traffic.

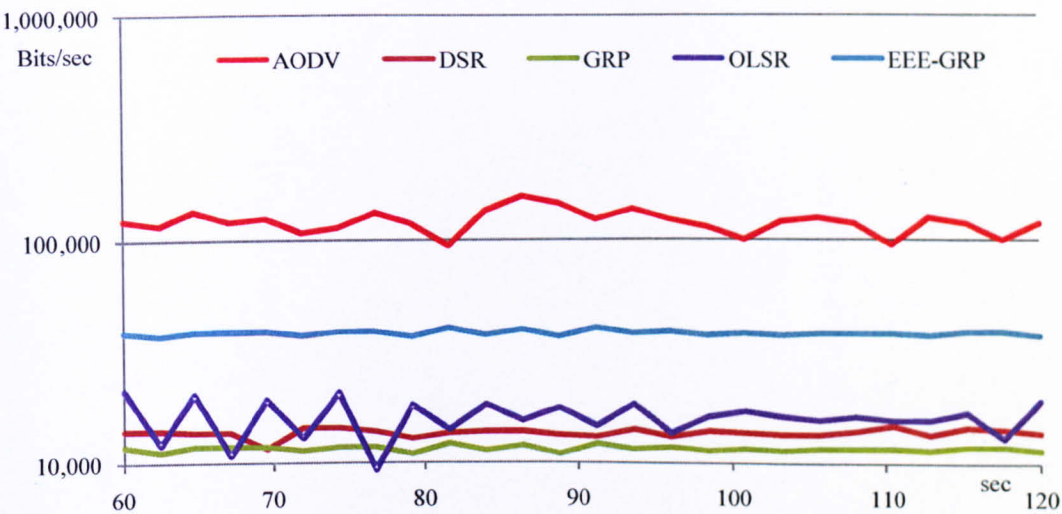


Figure 6.20 Signalling Rate Comparison for 25 Nodes with FSPL Model

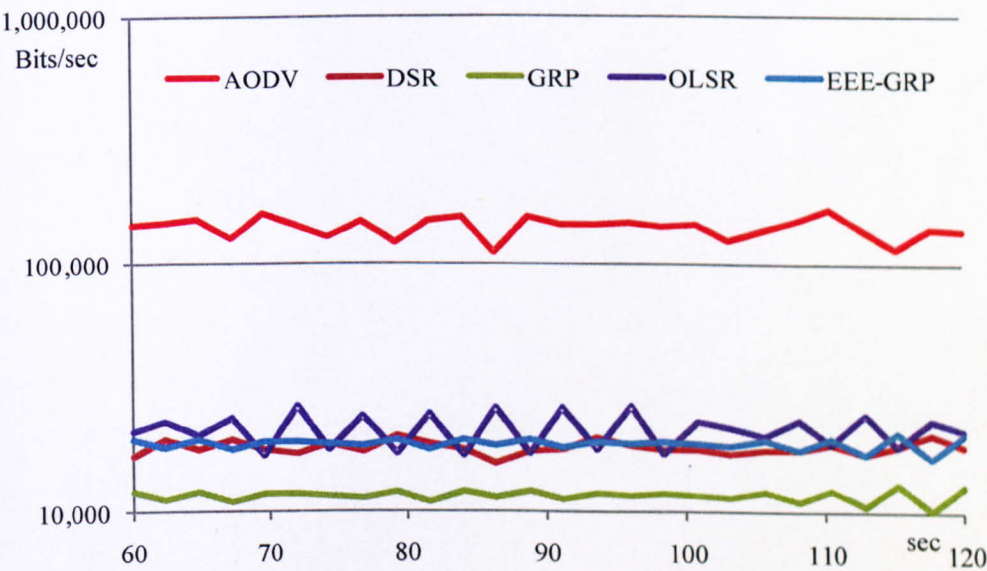


Figure 6.21 Signalling Rate Comparison for 25 Nodes with NonFSPL Model

In Figure 6.22, the number of nodes was doubled to 50 nodes. The number of neighbours for each node was generally increased in both FSPL and NonFSPL scenarios.

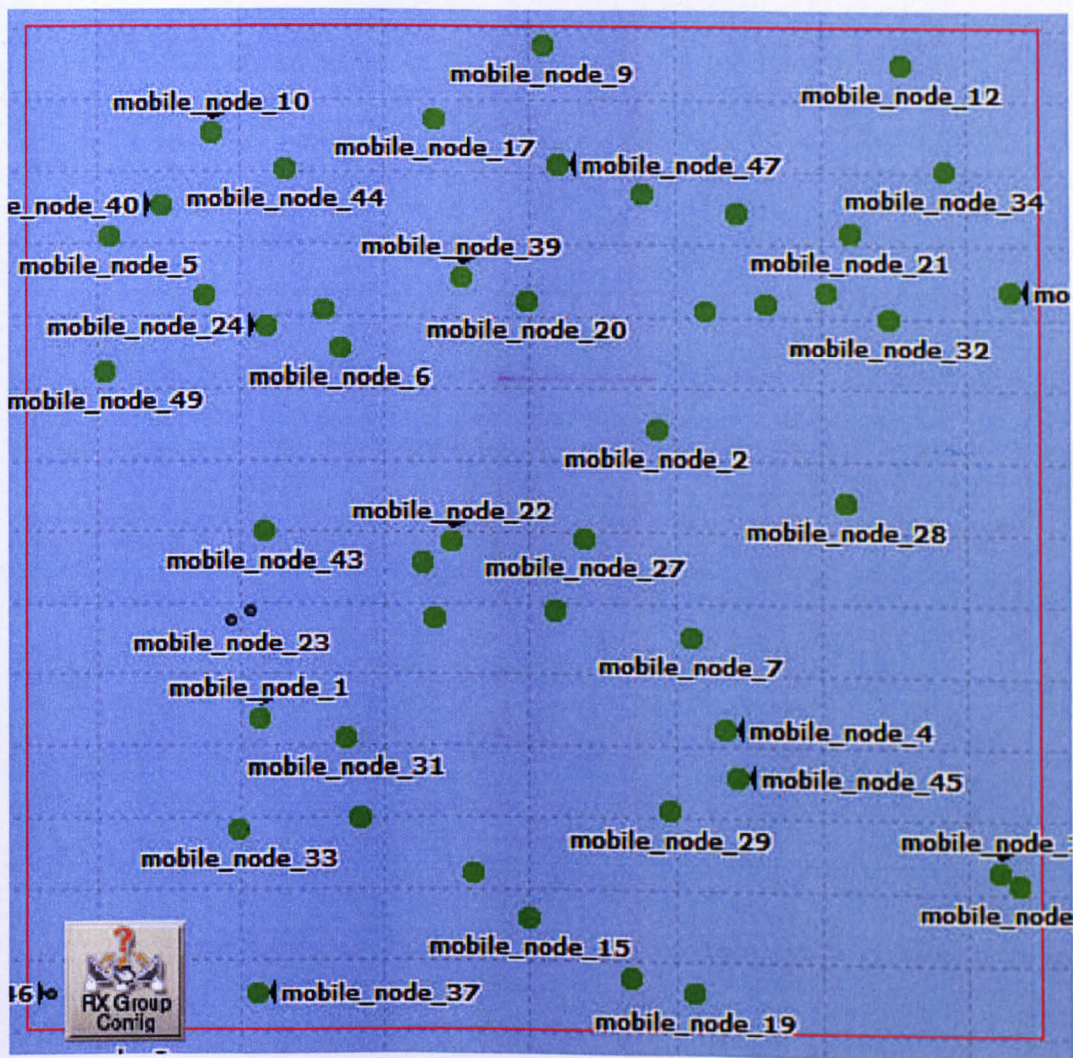


Figure 6.22 Simulation Scenario with 50 Nodes

From the results shown in Figure 6.23 with FSPL model and Figure 6.24 with NonFSPL model, a similar trend to that observed in the previous simulation was observed. GRP and AODV are still the lowest and highest in signalling overhead. Routing traffic sent by DSR and OLSR increased accordingly in NonFSPL scenario while it dropped heavily for EEE-GRP.

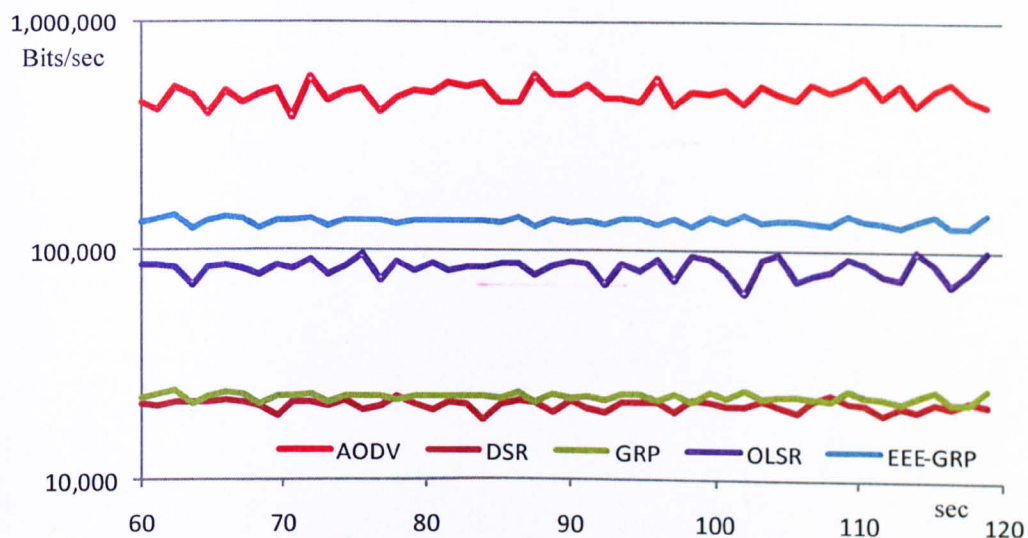


Figure 6.23 Signalling Rate Comparison for 50 Nodes with FSPL Model

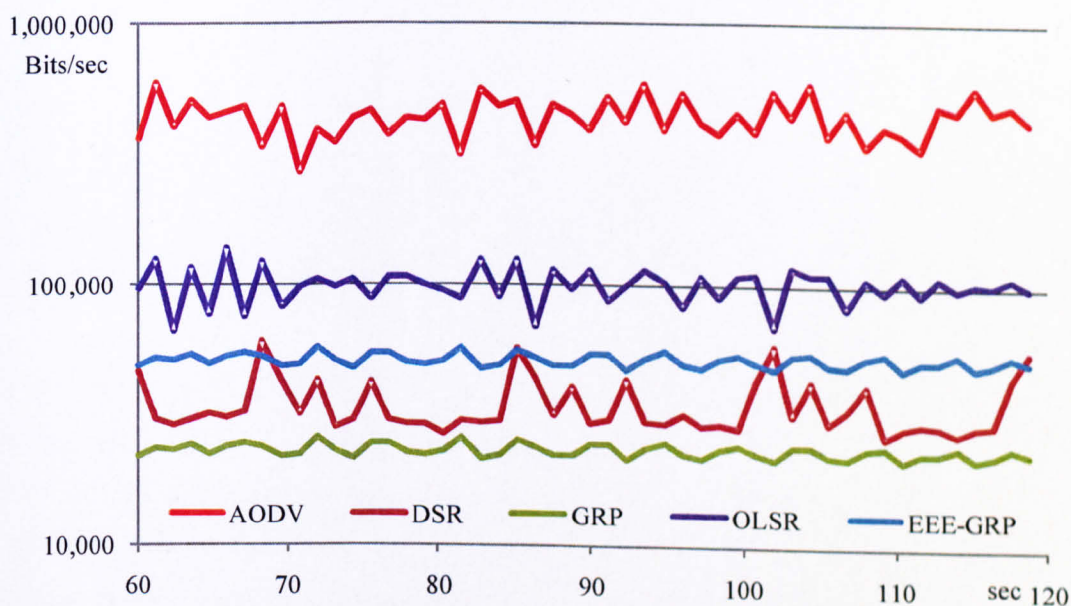


Figure 6.24 Signalling Rate Comparison for 50 Nodes with NonFSPL Model

The total number of nodes was increased to 100 as shown in Figure 6.25. A NonFSPL model wasn't applied in this network due to the long simulation time required for AODV and DSR. We observed that AODV and DSR suffered from the high node density and their signalling overhead became higher than other routing protocols.

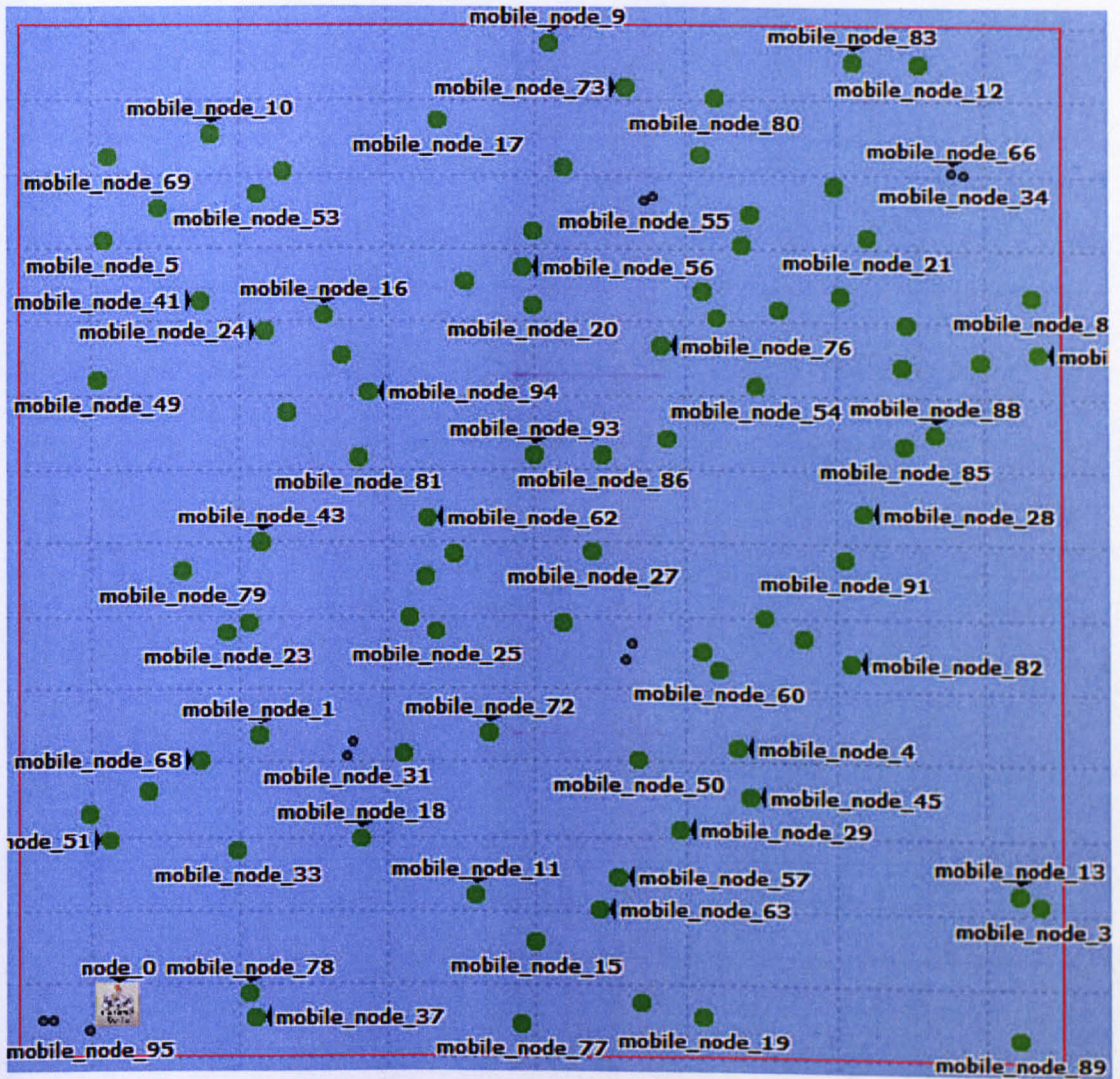


Figure 6.25 Simulation Scenario with 100 Nodes

As we can see from the results shown in Figure 6.26, DSR couldn't cope with dense network and its routing traffic became even higher than AODV. The signalling overhead of GRP is only affected by the number of nodes, so it increased proportionally with the higher node density. OLSR and EEE-GRP also showed a notable increase in routing traffic. However, lower signalling for EEE-GRP is expected with a NonFSPL model while other routing protocols except GRP will have higher routing traffic.

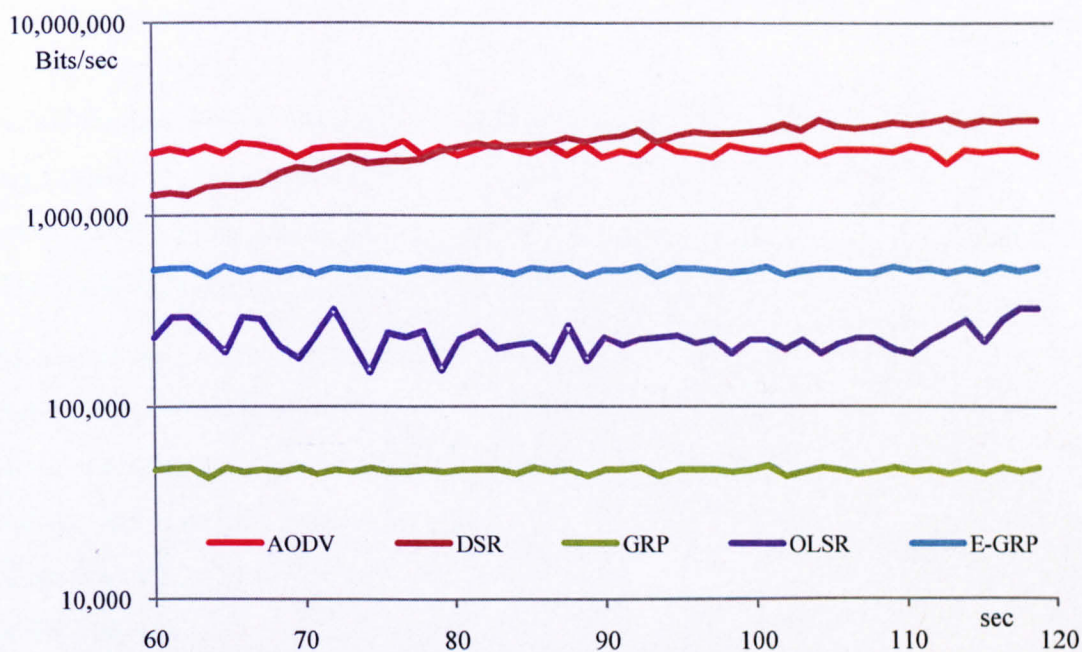


Figure 6.26 Signalling Rate Comparison for 100 Nodes with FSPL Model

Figure 6.27 shows the results of average routing traffic sent at different node density and transmission range for EEE-GRP.

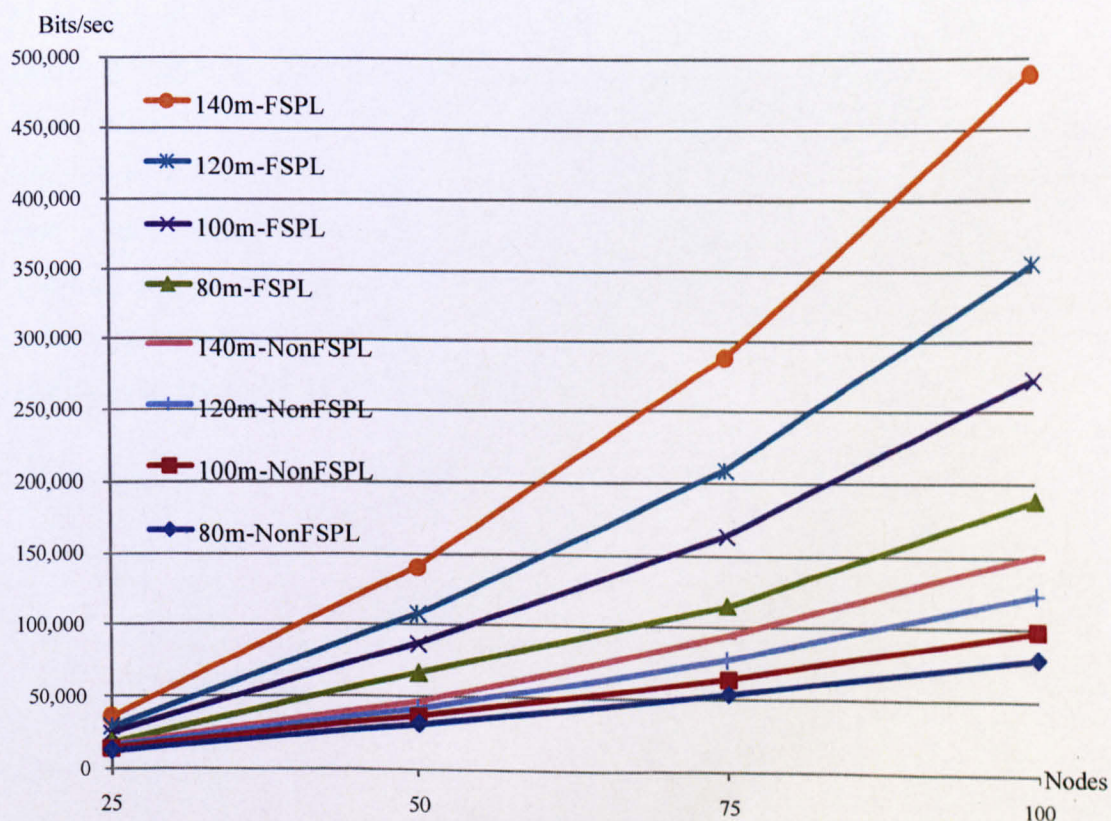


Figure 6.27 Results Comparison with Various Node Density & Tx Range for EEE-GRP

With the increase of network density, the routing traffic sent in the network increased rapidly. The average routing traffic sent by the network is the highest among different node densities with a transmission range 140m because the size of Hello message is large due to the increased number of neighbours for each node. When NonFSPL is used instead of the FSPL model, the network sent out less routing traffic due to the smaller size of the Hello messages needed for fewer neighbour nodes.

As shown in previous results, the signalling overhead became very high in a high density network. However, this problem could be resolved by optimizing the size of the Hello message through an intelligent neighbour node selection method. In such a scheme only a certain number of candidate nodes will be selected among a large number of neighbours using more specific criteria such as the location of the nodes, the quality of the link etc.

6.5 Conclusion

In this chapter, signalling processes for the proposed routing protocol are introduced. With the enhanced signalling system, the routing protocol is able to obtain more information to assist routing determination. The simulation results showed that the signalling overhead can be reduced significantly when the transmission range reduces which reduces the number of neighbours for each node. Simulation results also gave a comparison of the overhead required for the proposed protocol (EEE-GRP) with that of other established protocols under a variety of different network conditions. The proposed protocol is seen to require lower signalling overhead than AODV in all circumstances and compares favourably with other protocols under a variety of network conditions in particular in NonFSPL path loss scenarios.

Chapter 7 Conclusions and Future Work

7.1 Conclusions

Mobile Ad-hoc networks have attracted growing research interest over the last 10 years as they offer a flexible means of communication without the need for fixed infrastructure. This will have advantages for applications including communications for the emergency services, military communications, conferences, vehicular and ship to ship communication.

Chapter 2 reviews the state of the art in mobile Ad-hoc networks and the underlying wireless technologies upon which they are based. A key feature of Ad-hoc networks is that individual nodes can act as relays to support multi-hop transmission between source and destination nodes which requires each node to have a routing capability. A summary of existing proactive, reactive, hierarchical and geographic protocols is presented. Geographic protocols have the advantage that they use knowledge of the location of the nodes to simplify the search for a route from source to destination. It is noted that there is growing interest in the use of geographic protocols because the cost of location identification using GPS technology is falling, so that it is now feasible to include this capability in wireless Ad-hoc network nodes. A number of geographic protocols have been proposed for Ad-hoc networks but these protocols use position information as the only metric and ignore link quality. They seek a path with the smallest number of hops or the shortest distance but do not take account of energy consumption. As wireless nodes, particularly mobile nodes, are battery operated, energy consumption is an important factor. The primary objective of this thesis, therefore, is to develop an energy efficient geographic routing protocol for mobile Ad-hoc networks.

Chapter 3 introduces the OPNET Modeller simulation software tool that is used to simulate the Ad-hoc network. This tool is an event driven simulator that includes 802.11 wireless models and also several of the most common routing protocols used for Ad-hoc networks. The software can also be adapted to include new features and functions specific to this project. The default path loss model in OPNET is the free space model. This has been adapted to include a random path loss model to provide a more accurate analysis of the power required to communicate between each node. The routing

protocols developed in this project have also been modelled using OPNET so that the performance can be analysed and compared to existing protocols.

Chapter 4 describes a new, energy efficient geographic routing protocol (EE-GRP). This scheme seeks to find the lowest power route from source to destination. The principle of this protocol is that multiple short hops may require a lower transmission power than a single long hop. If every possible route were to be analysed, then the processing would be very complex, so this protocol reduces the number of routes analysed by using a 'gain region' and a 'relay region', identified using knowledge of the location of nodes obtained from GPS units in each node. If a node in the gain region is used as a relay node, then the transmission power from source to destination using this relay can be less than that of a direct link to the destination. The relay region can then be defined for relay node selection according to the distance requirement from the source and destination node. The node in the relay region is selected based on the lowest path loss from the source node. For longer links, multiple relay nodes can be located on a hop by hop basis. Each relay node requires power for processing and so the lowest power end to end route is a balance between the reduced transmission power and the increase in processing power for multiple hops.

An OPNET model has been developed to simulate the performance of the EE-GRP protocol. The model uses a 350m x 350m size network with 240 randomly located nodes. The end to end transmission power for the selected route has been calculated and compared to the power that would be required for the route that would be selected by a conventional geographical routing protocol. The results show that, for a transmission range of 140m, the routes selected by the EE-GRP protocol require 33% of the transmission power required by the conventional geographical routing protocol.

It is shown that the power saving scales with the transmission range because if the transmission range increases then the number of nodes in the gain region increases which increases the number of possible routes that are analysed. So for a transmission range of 170m the EE-GRP protocol only requires 9% of the transmission power required by the conventional geographical routing protocol.

Moreover, a random battery level model is applied for each mobile node when the lifetime metric is used to evaluate the routing performance. This time the EE-GRP

shows its greater advantage in that the lifetime increases by a factor of 14 over the conventional geographic routing protocol.

The disadvantage of the EE-GRP protocol is that in order to maintain the hop count from the source to the destination the protocol can lead to a very small gain region, which limits the number of nodes available for choice as a relay node. This may not enable the lowest energy route to be found and sometimes fail to find a relay node. Chapter 5 describes an enhanced energy efficient geographic routing protocol (EEE-GRP) which sets a minimum forward distance for each hop which ensures that the relay region does not become too small based on an optimised hop count obtained from a hop count decision mechanism. In addition, based on the density of nodes in the network, the number of hops is calculated to give at least three nodes in the relay region.

Results of network simulations using OPNET Modeller indicate that the energy consumption due to the transmission power for routes using the EEE-GRP protocol is slightly larger than the EE-GRP protocol for routes with a small number of hops (3-4 hops). For routes with larger hop counts (5-8 hops), the EEE-GRP protocol again selects routes with a slightly higher energy consumption due to node transmission power, but it has the advantage that the selected routes have a smaller number of hops. This is important because the overall energy consumption comprises the transmission power and the processing power of each node in the route, and the processing power is typically an order of magnitude larger than the transmission power. So when the processing power of each node is included in the total energy calculation, then the overall energy consumption can be reduced by approximately 20% using the EEE-GRP protocol compared to the EE-GRP protocol. This leads to a corresponding increase in the time a route can function on a single battery charge.

The new routing protocol proposed in this thesis requires a new signalling process to distribute the required information between the nodes in the network. Chapter 6 analyses the signalling requirements for the proposed protocol. Each node initially floods the network on a beacon channel to broadcast a node identifier and the co-ordinate information. Simulation indicates that this information should be repeated three times to cope with possible collisions and ensure all nodes receive the information. Each node broadcasts a Hello message to its neighbour nodes at regular intervals. This message includes battery level and link quality information. A key feature is that it sends information about itself and its neighbour nodes. Each node then builds a table of

one hop neighbours and two hop neighbours which is used to establish the optimum route.

OPNET modeller has been used to analyse the amount of signalling data required for the new signalling process proposed in this thesis for EEE-GRP and this has been compared to the signalling required for other Ad-hoc routing protocols (AODV, DSR, OLSR, regular GRP). The results show that AODV requires the largest amount of signalling information and DSR and regular GRP the lowest (about 20 times lower). EEE-GRP requires approximately seven times more signalling data than DSR and regular GRP. This is because of the extra information required in the Hello message to find the most energy efficient route. If the traffic source packet inter-arrival time is reduced (e.g. more packets are generated), then the signalling for the reactive protocols increases, but the signalling for the proactive protocols, including EEE-GRP, stay constant.

The average signalling overhead was studied under different network traffic load to evaluate the performance of the proposed protocol. Although the amount of signalling required to implement the EEE-GRP routing protocol is larger than some of the other protocols, the amount of energy used to provide this signalling is relatively small (approximately 10%) compared to the energy required for the data transmission in the same period during the simulation. The signalling messages used a constant transmission power while the transmission power for the data traffic can be further reduced according to the path loss information obtained from the signalling process. So the benefits gained from the reduced energy required for the traffic transmission outweighs the increase due to signalling. So overall the energy consumption of the EEE-GRP protocol is lower than other protocols.

7.2 Original Contributions

The original contributions presented in this thesis are as follows:

- 1) A new geographical Ad-hoc network routing protocol has been developed which uses the concept of a gain region to minimise the energy consumption of the route from source to destination using relay nodes. The energy consumption using this protocol is shown to be 30% of a conventional geographical routing protocol.

- 2) An improvement to the proposed routing protocol has been designed to ensure the gain region does not become too small. The enhanced protocol reduces the number of hops and hence the overall energy consumption of the selected routes is reduced.
- 3) A new model has been developed for the EE-GRP protocol using OPNET Modeller to simulate the network performance.
- 4) A non-free space path loss model has been included in the simulation model with a random loss between each node in the network.
- 5) A new signalling process has been proposed for use with the proposed new geographical Ad-hoc routing protocols.
- 6) The energy consumption and lifetime of the route for the EEE-GRP protocol has been calculated and analysed and it is shown to be lower than that of other Ad-hoc network geographic routing protocols.

7.3 Future Work

Further work could be carried out in the following areas:

- 1) A prototype network using the proposed routing protocol can be constructed and evaluated to check that the benefits predicted by the simulation can be realised in practice.
- 2) The analysis described in chapter 6 compares the signalling performance of the new geographical routing protocol to the existing non-geographical protocols (DSR, AODV and OLSR). A similar comparison can be carried out for the data transmission performance.
- 3) Wireless nodes cannot transmit and receive at the same time, so the throughput of multi-hop routes is affected by the number of hops in the route. The proposed EEE-GRP protocol can be extended to include the calculation of throughput as an additional metric for selecting the optimum route.

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Published work

1. H. Cao, G. Childs, and P. Ball, "Ad-hoc Wi-Fi coupled with UMTS FDD mode to provide Intelligent Relaying", proceedings of the Fifth International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), Patras, Greece, pp. 220-223, 19-21 July 2006.

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Presentation Award

1. H. Cao, G. Childs, and P. Ball, 'A Novel Geographic Routing Protocol for Mobile Ad-hoc Networks', Present Around the World Final, the IET Younger Members Conference, Glasgow, 09 Nov 2006

A Novel Geographic Routing Protocol for Mobile Ad Hoc Networks

Student: Hui Cao

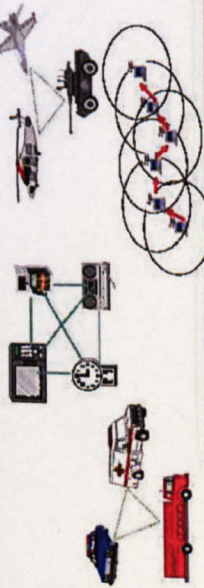
Supervisor: Dr. Geoff Childs
Dr. Peter Ball

Outline

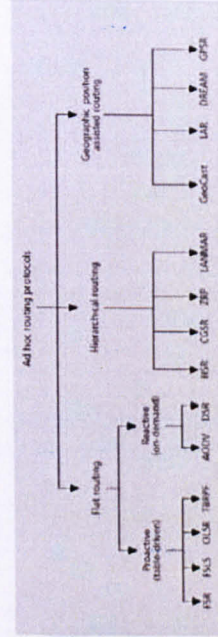
- Introduce Mobile Ad Hoc Networks (MANET)
- Geographic Routing Protocols
- Concept of Gain Region
- A Novel Forwarding Strategy
- Conclusion

What is Mobile Ad Hoc Networks?

- Collection of mobile nodes forming a temporary multi-hop wireless network
- No fixed network infrastructure
- No centralized network administration
- Nodes function as both hosts and routers

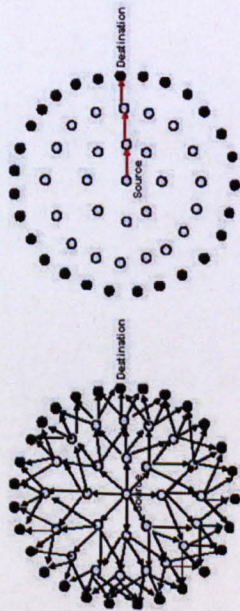


Routing Protocols in MANET



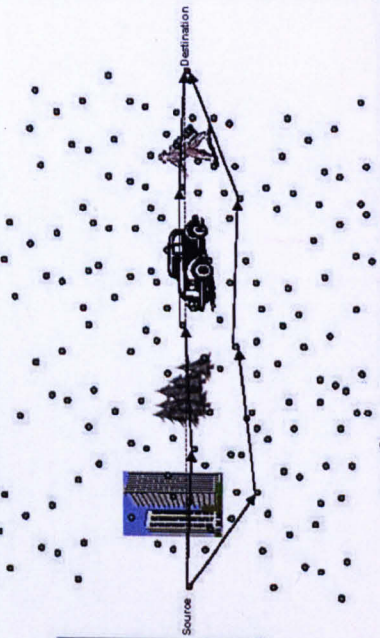
- Geographic Position Information Assisted Routing Protocols
- It uses specific geographic information to specify the destination, rather than logical node address

Routing Protocols Comparison



Non-Geographic Routing Geographic Routing

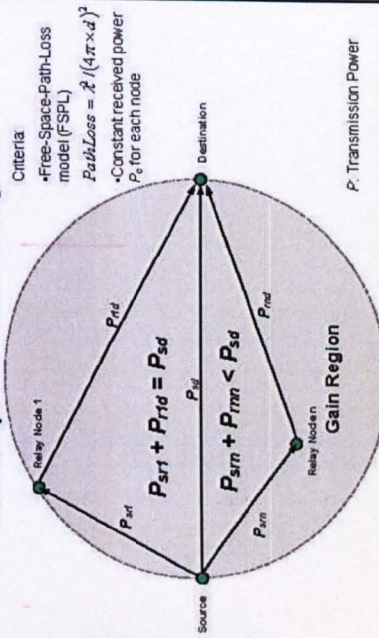
Shortest Route = Ideal Route ?



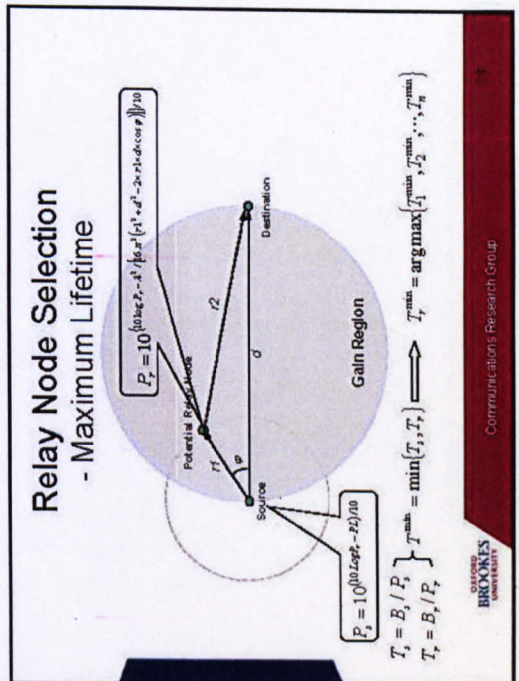
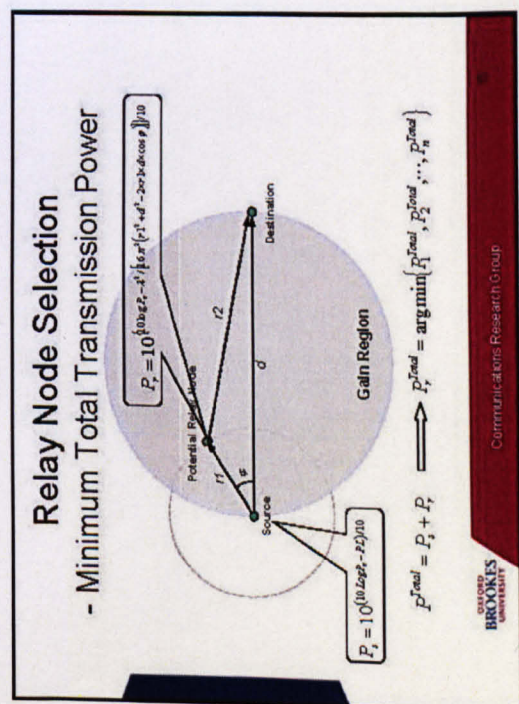
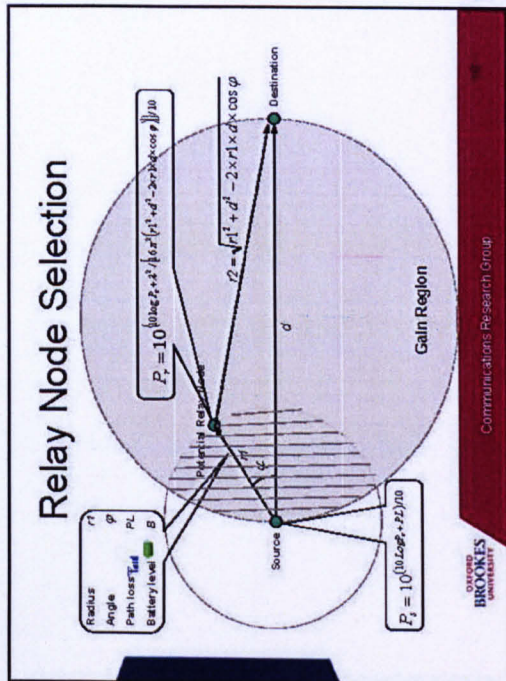
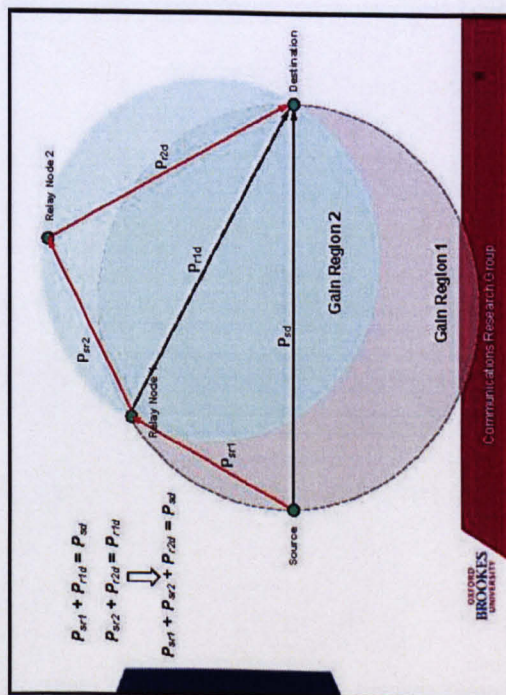
Motivation

- Conventional protocols use free space propagation model which assumes the ideal propagation condition. However the signal is degraded by surrounding objects.
- Routing directions should be chosen within a gain region in a dynamic manner in order to avoid shadow areas and to be adaptable to the real time link conditions.

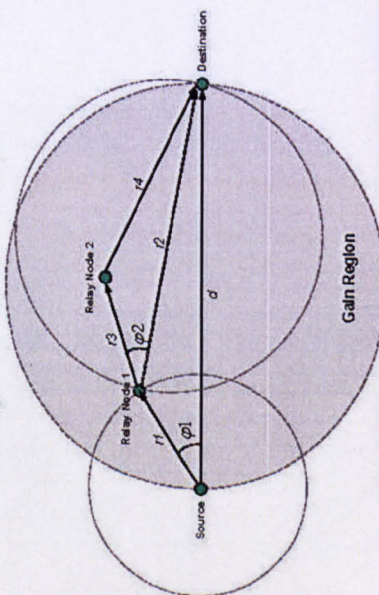
Concept of Gain Region



P : Transmission Power

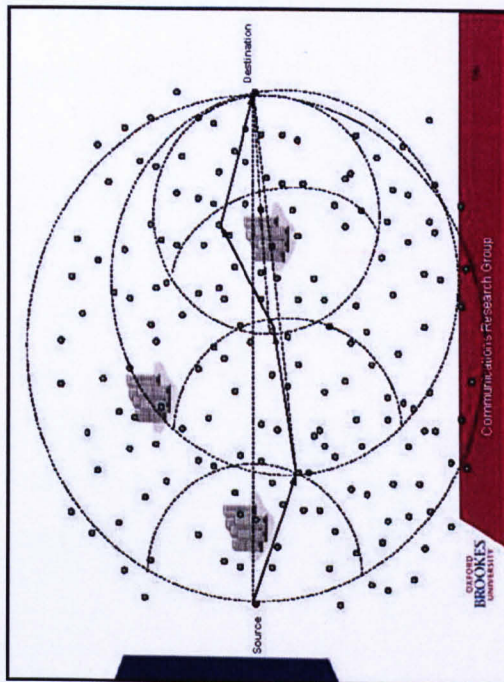


Relay Node Selection



Conclusion

- Use a longer distance with line-of-sight (LOS) route instead of a straight line with none-line-of-sight (NLOS) route.
- Adapting the searching range for the next hop to control hop counts and data rate.
- By a discrete-approaching algorithm, each hop is optimised in term of path loss, battery life and deviation angles.
- The total transmission power is therefore minimised and the network performance is significantly improved.



Thanks... 😊
Any Questions?

Appendix A: Creating a Wireless Network on OPNET

A blank scenario can be created by choosing File>New from the menu as shown in Figure A.1 and then follow the Startup Wizard.

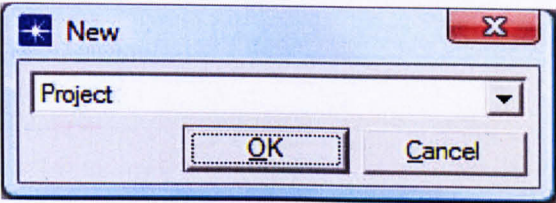


Figure A.1 Startup Wizard

After entering project name and scenario name, choose Create Empty Scenario from Initial Topology as shown in Figure A.2.

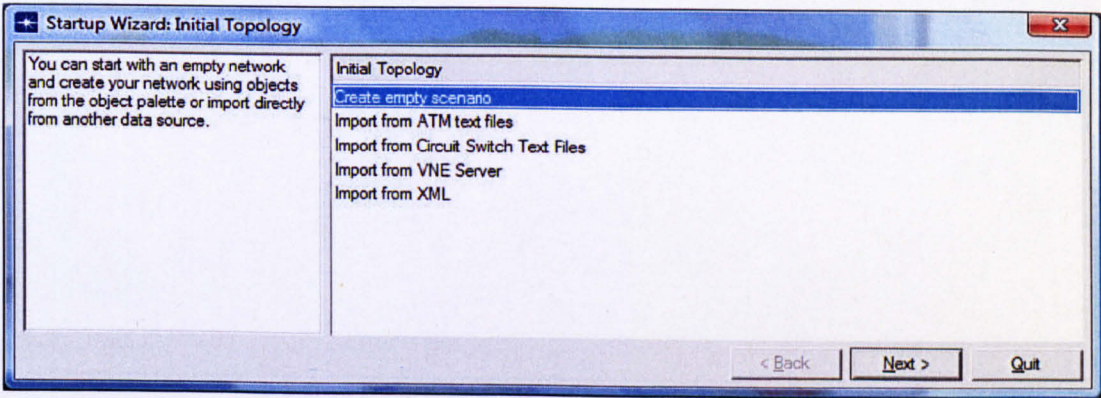


Figure A.2 Initial Topology

Next step is to choose network scale. The size of network can be chose from world, enterprise, campus, office, logical or from maps as shown in Figure A.3.

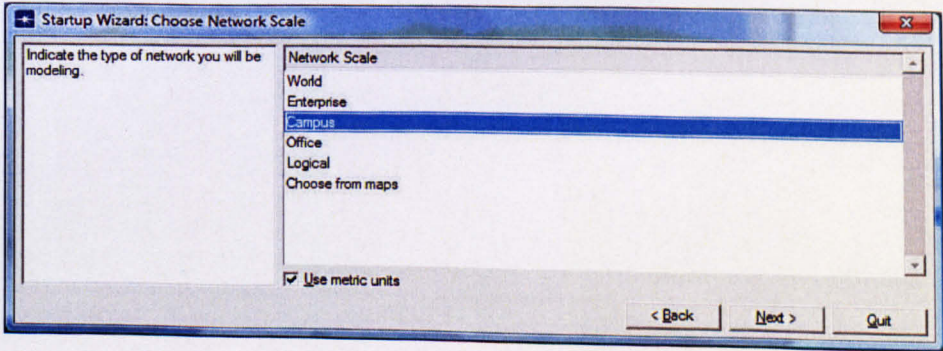


Figure A.3 Choose Network Scale

The network size can be specified by defining X and Y span and the units as shown in Figure A.4.

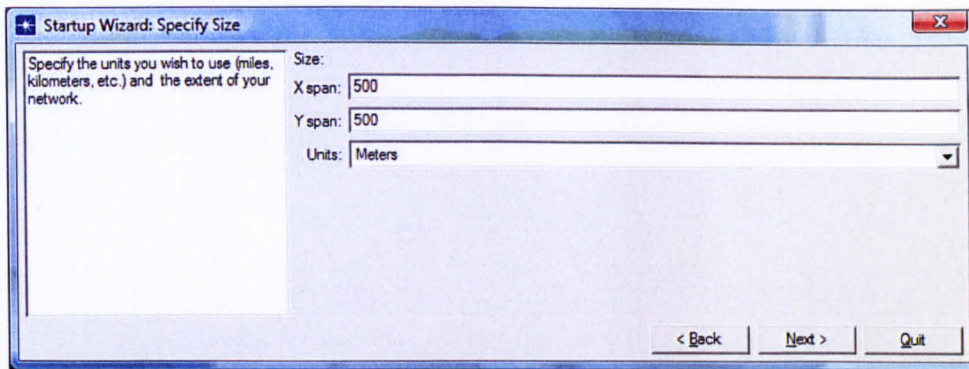


Figure A.4 Specify Size

In Figure A.5, MANET or other model family can be included next from 'Select technologies'.

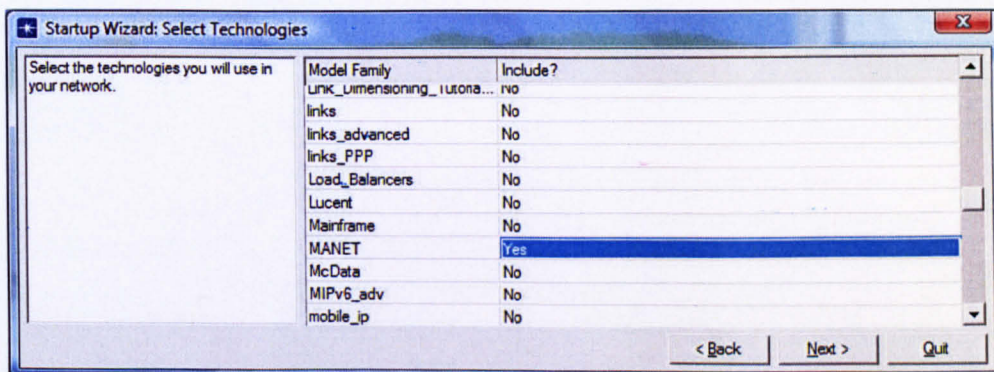


Figure A.5 Select Technologies

After review and choose finish as shown in Figure A.6, a blank scenario is then created.

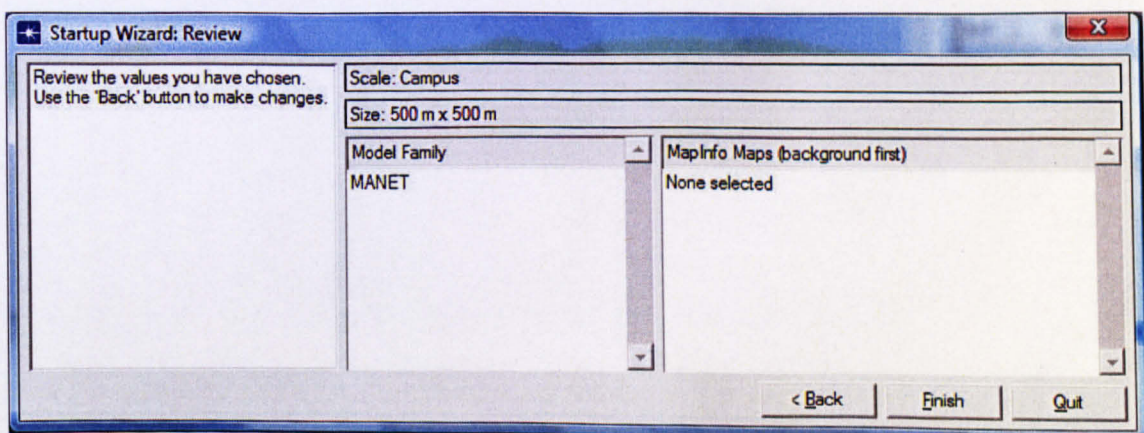


Figure A.6 Review of Startup Wizard

A wireless network can be created manually by opening the 'Object Palette' as shown in Figure A.7, the MANET nodes can be dragged and dropped into the project editor workspace.

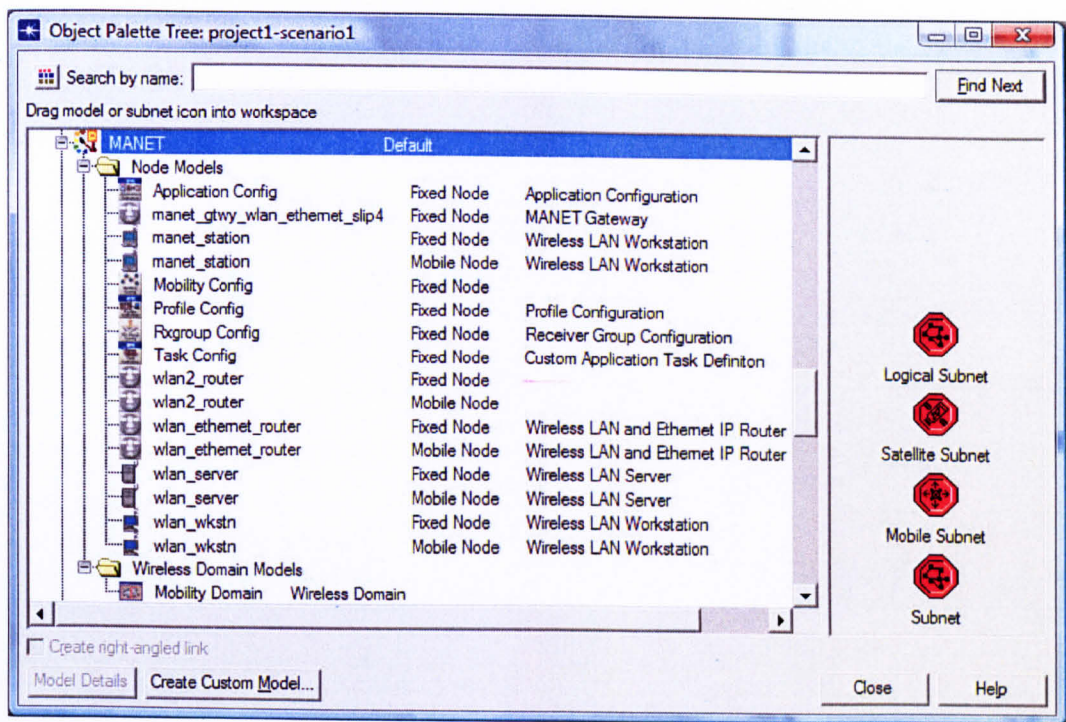


Figure A.7 Object Palette

The preferred method for automatically deploying wireless networks is through either ‘Rapid Configuration’ or ‘wireless network deployment’ wizard.

The ‘Rapid Configuration’ function can be found from ‘Topology’ menu. The first step to set up the network is to choose a proper topology for the network from bus, mesh, ring, star, tree and unconnected net as shown in Figure A.8. The unconnected net is selected here for wireless network since other topologies are only suitable for wired network.

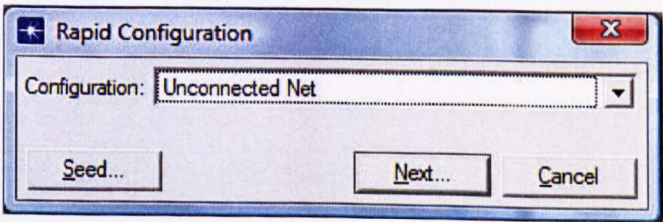


Figure A.8 Topology Selection for Rapid Configuration

A seed can be randomly generated or manually entered as shown in Figure A.9. By using different seeds, the distribution of the nodes also changes.

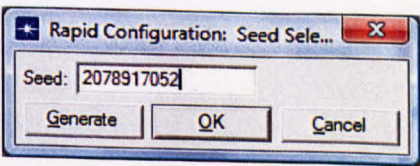


Figure A.9 Seed selection

In Figure A.10, the MANET node model and number of node will be selected and their type with either mobile or fixed. The placement will define the area where the nodes will be placed. A wireless network will be created after this configuration.

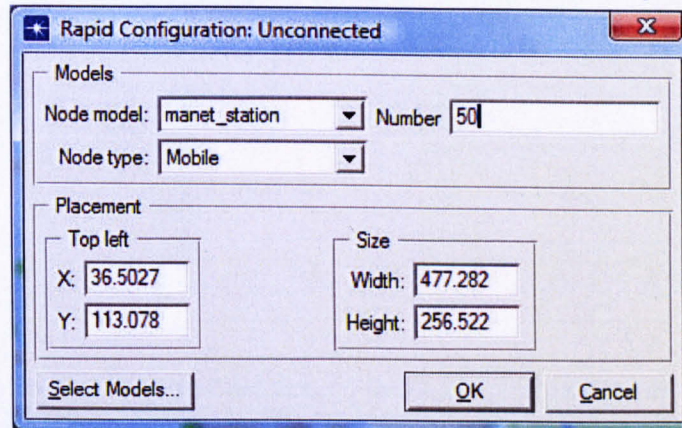


Figure A.10 Models and Placement Configuration

'Wireless Network Deployment' wizard is another option to build, configure, and deploy a wireless network segments in a quick and easy way.

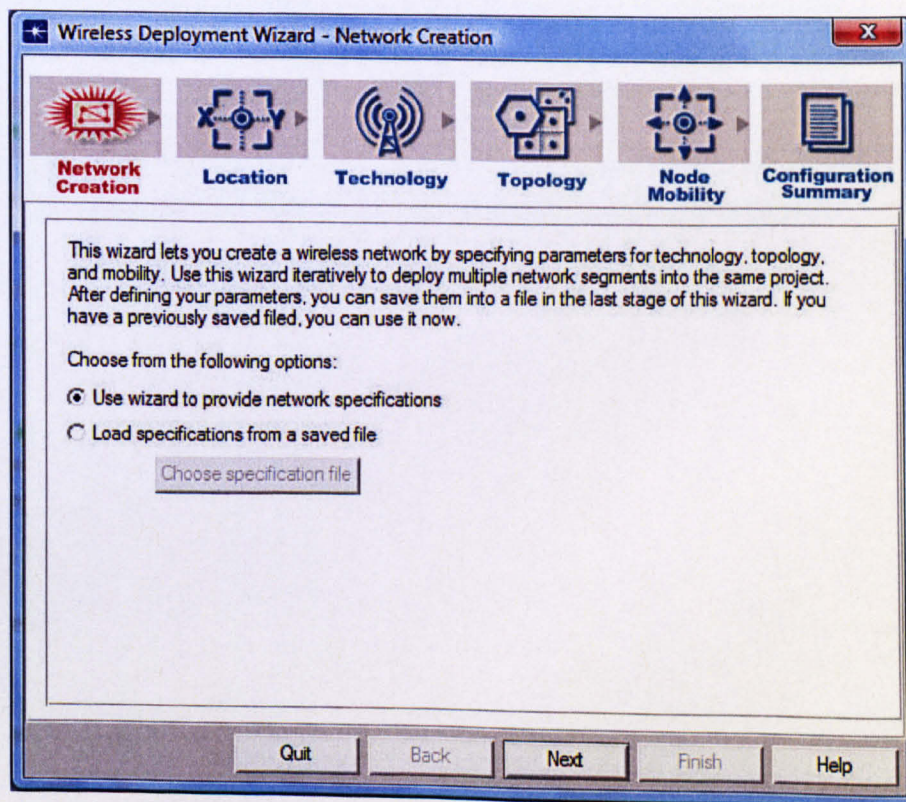


Figure A.11 Network Creation for Wireless Deployment Wizard

Figure A.11 shows the network creation method for wireless deployment wizard. Selection of "Use wizard to provide network specifications" will confirm of use the wizard to configure a new network.

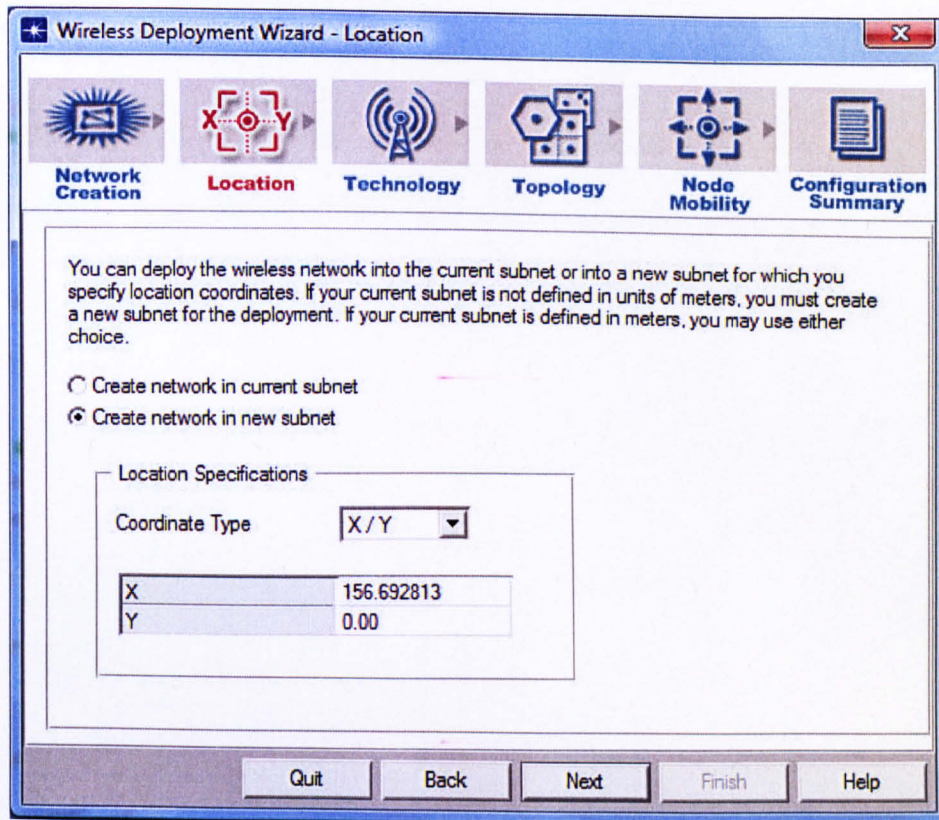


Figure A.12 Location for Wireless Deployment Wizard

In Figure A.12, the location coordinates will be specified in which the new network will be deployed. The technology that will be used is defined in the next step as shown in Figure A.13. The WLAN (Ad-hoc) technology is selected and the parameters such as node transmission power, operation mode, data rate and ad-hoc routing protocol for each node are defined.

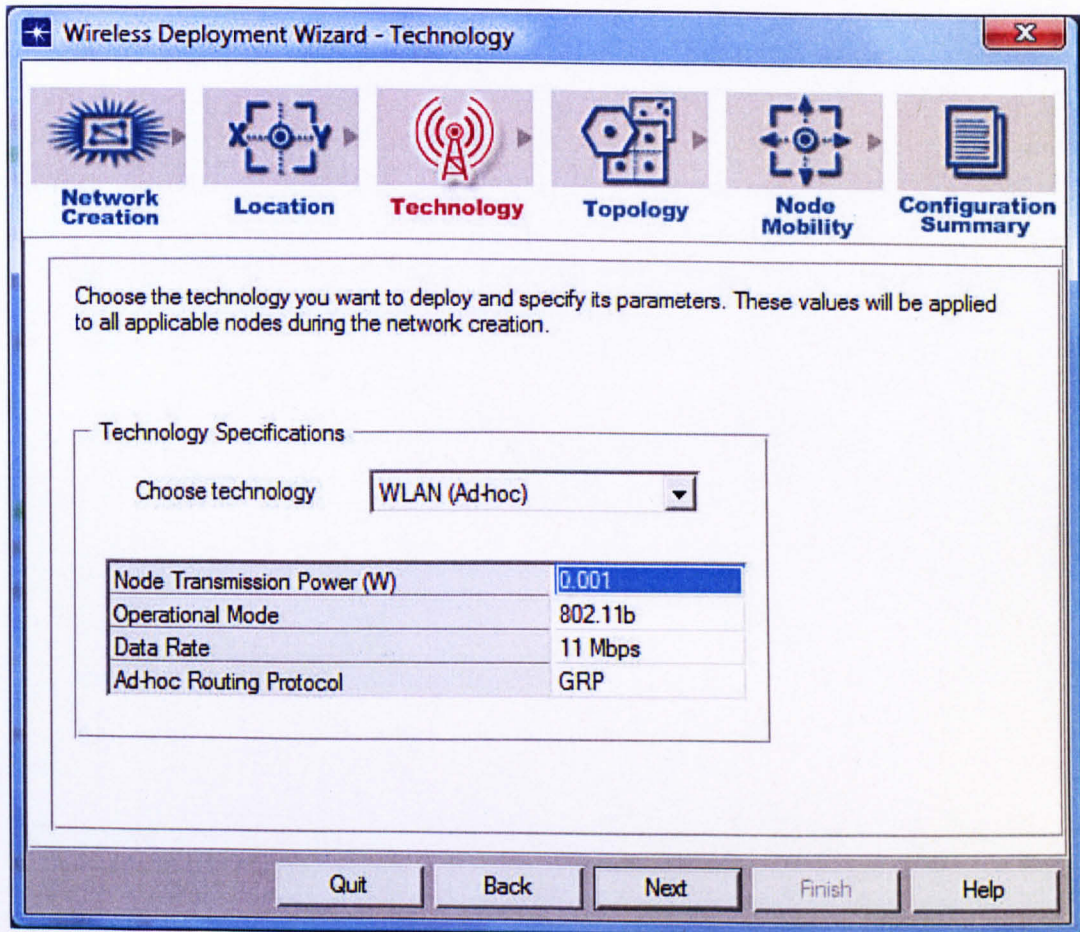


Figure A.13 Technology for Wireless Deployment Wizard

Figure A.14 shows the topology configuration, a geographical overlay can be specified as follows. However, for an Ad-hoc network only the 'None' overlay can be chose.

- None—Define the area in square meters.
- Cell (Hexagon)—Define the number of cells and the cell radius in kilometers.
- Cell (Square)—Define the number of cells and the length of the squares in kilometers.

"Mobile Node Placement Specifications" can be chose from random, grid or circular. If grid fashion is preferred, the number of rows and columns in the grid need to be provided.

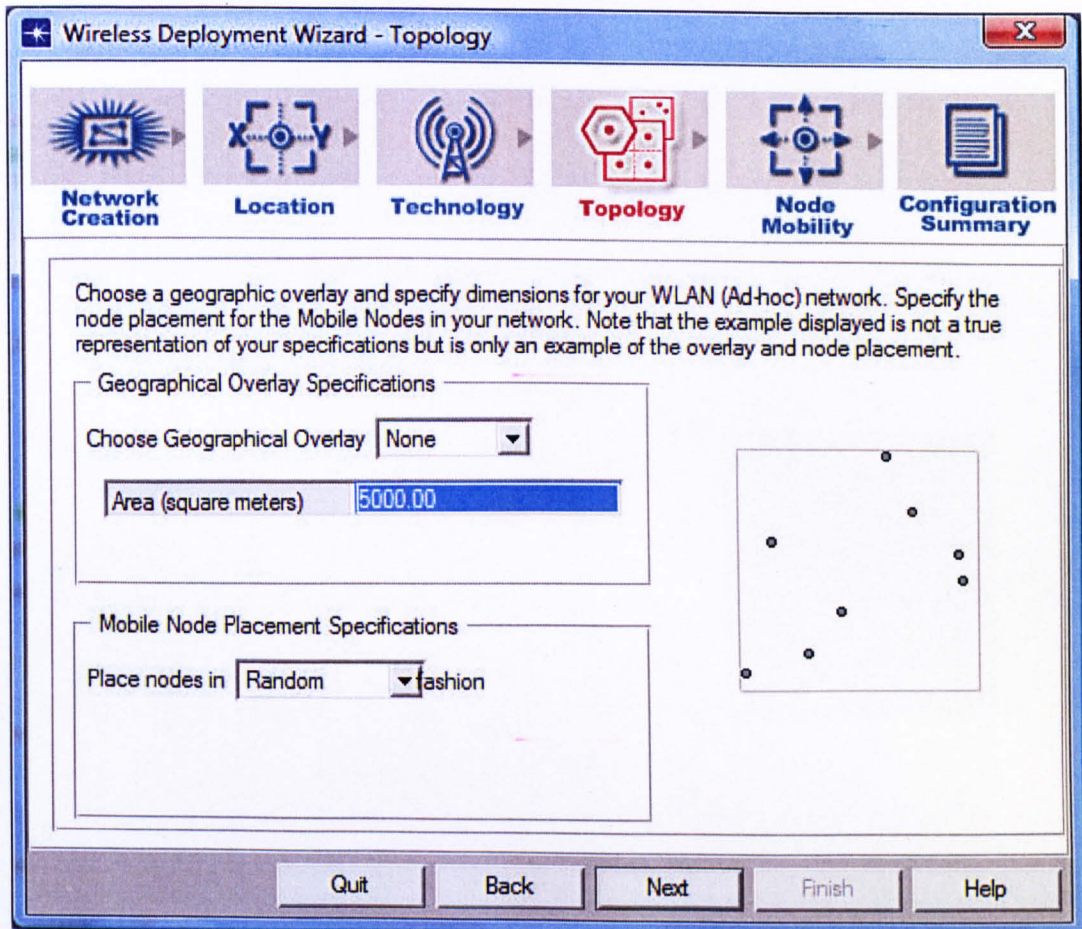


Figure A.14 Topology for Wireless Deployment Wizard

The node model, count, and node name prefix are specified as shown in Figure A.15. In this case, `manet_station` will be selected as the node model. The 'count' parameter defines the number of node that will be deployed in the network. The Node Name Prefix prepends a text string to a generated node name, assuring unique node names in this network. The 'access point' is not viable for Ad-hoc option.

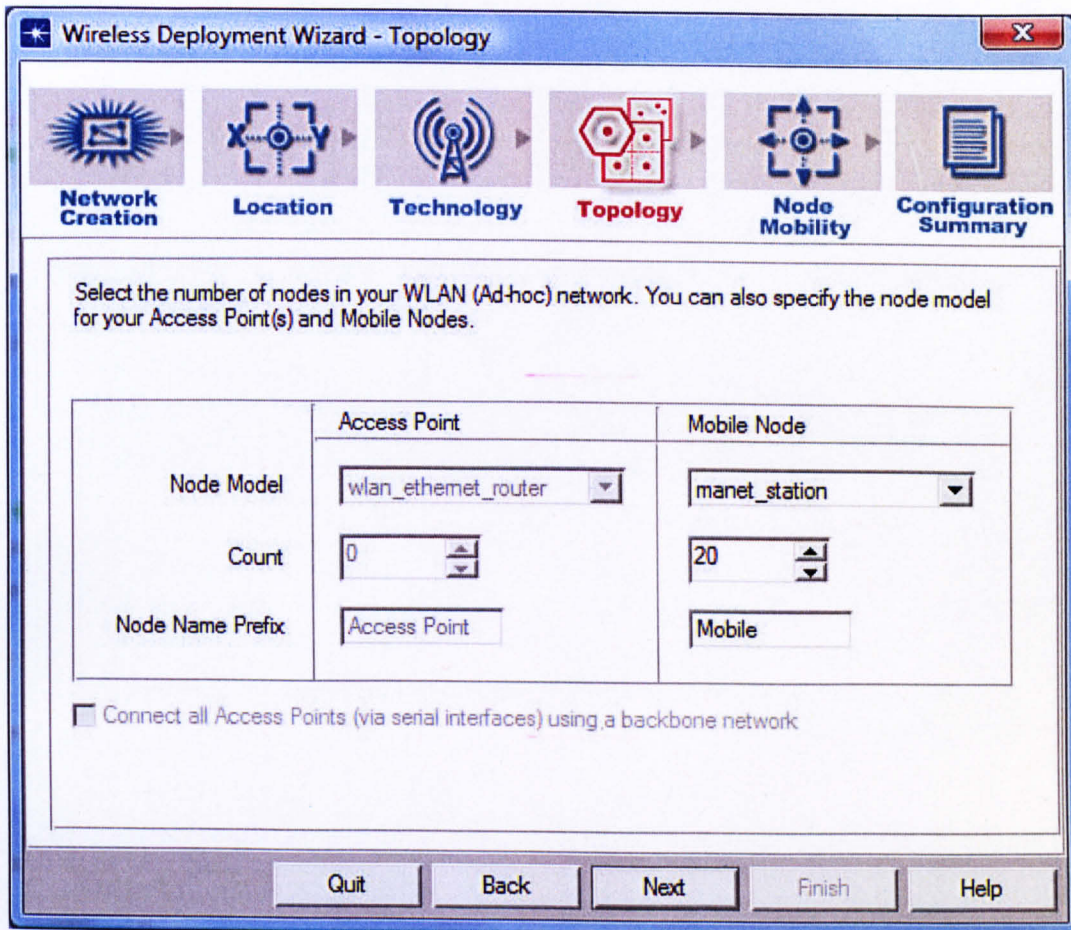


Figure A.15 Node Model Selection for Wireless Deployment Wizard

Node mobility parameters for the wireless network can be specified as shown in Figure A.16. More rows can be applied to support multiple mobility profiles.

- Trajectory Information. 'Random Waypoint (Auto Create)' is the default setting. A mobility profile or a trajectory file can also be applied.
- Number of nodes. A number that up to the total number already specified for this network can be applied the trajectory information.
- Speed defines the movement speed of the nodes in meters per second.
- Area of Movement can be selected from 'within the network' for Ah-hoc network or 'within the cell' for an infrastructure network.
- Altitude of the nodes.

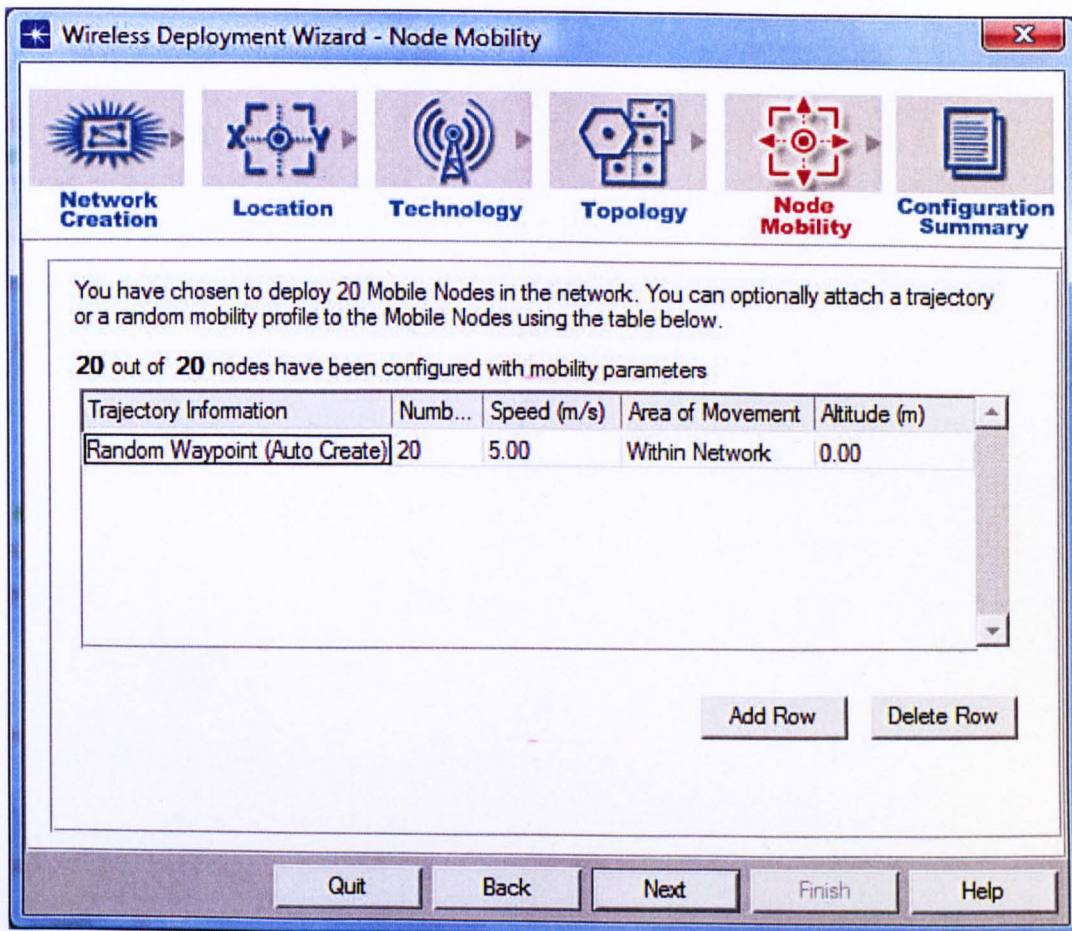


Figure A.16 Node Mobility for Wireless Deployment Wizard

A MANET is then created after review the 'Configuration Summary' showing the specifications previously defined.

Appendix B: Radio Transceiver Pipeline Stages

Radio links provide a broadcast medium and each transmission can potentially affect multiple receivers throughout the network model. In addition, for a given transmission, the radio link to each receiver can exhibit different behaviour and timing. As a result, a separate pipeline must be executed for each eligible receiver. The Radio Transceiver Pipeline consists of fourteen stages as shown in the figure below.

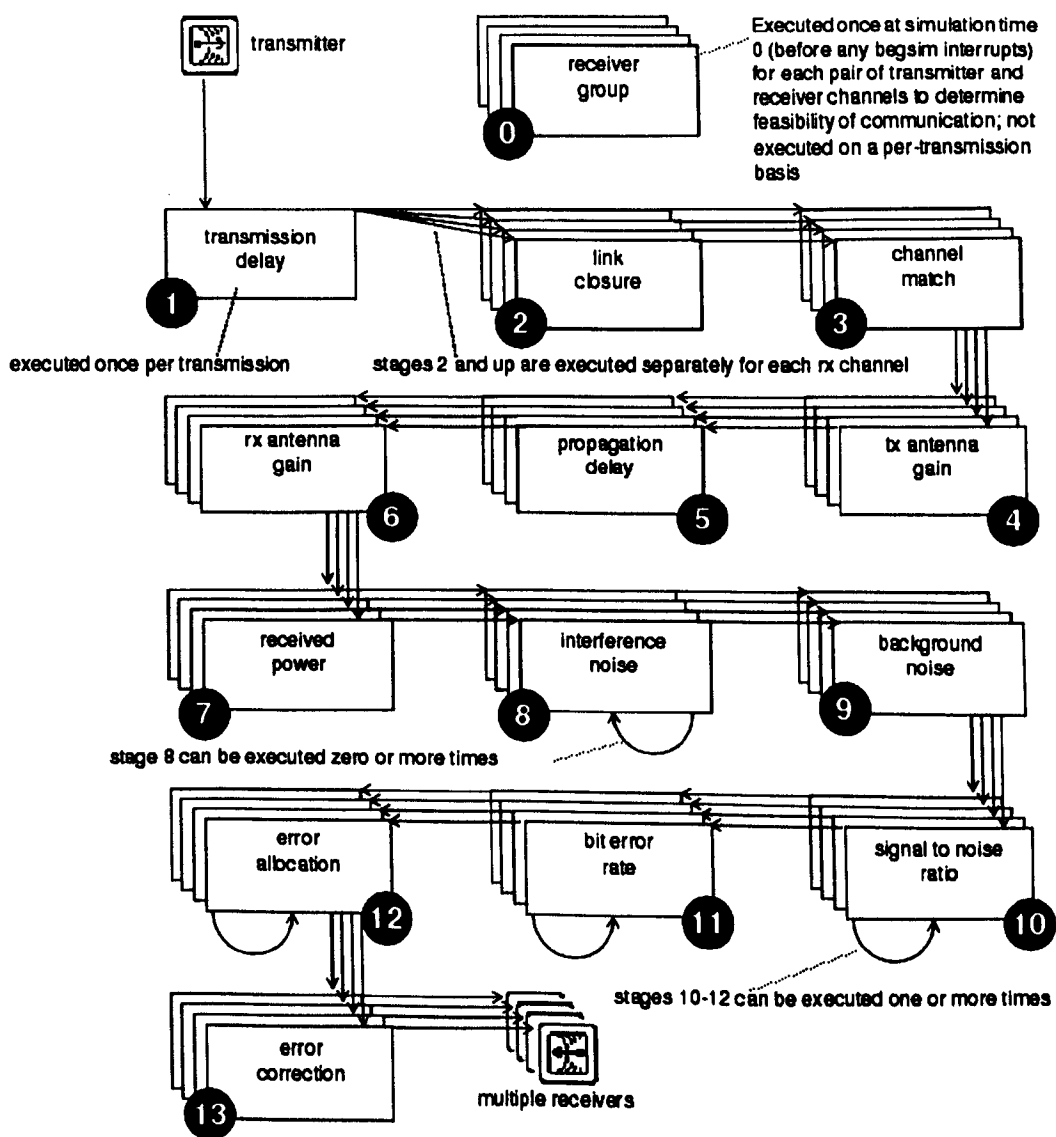


Figure B.1. Radio Transceiver Pipeline Execution Sequence for One Transmission

Stage 0 (receiver group) is invoked only once for each pair of transmitter and receiver channels in the network, to establish a static binding between each transmitter channel and the set of receiver channels that it is allowed to communicate with. The purpose of

stage 0 is to reduce computation to the minimum required set and filter out ineligible receiver channels.

Stage 1 (transmission delay) is used to compute a result that is common to all destinations, and therefore can be executed just once per transmission. This stage is invoked to calculate the amount of time required for the entire packet to complete transmission. This result is the simulation time difference between the beginning of transmission of the first bit and the end of transmission of the last bit of the packet.

Finally, each individual pipeline sequence might not fully complete, depending on the result of stage 2 (closure) which is specified by the "closure model" attribute of the radio transmitter, because this stage is responsible for determining if communication between the transmitter and receiver is possible on a dynamic basis. The purpose of this stage is to determine whether a particular receiver channel can be affected by a transmission. The ability of the transmission to reach the receiver channel is referred to as closure between the transmitter channel and the receiver channel. The goal of the closure stage is not to determine if a transmission is valid or appropriate for a particular channel, but only if the transmitted signal can physically attain the candidate receiver channel and affect it in any way; thus, this stage applies to interfering transmissions.

Similarly, stage 3 (channel match) is specified by the "chanmatch model" attribute of the radio transmitter classifies a transmission as irrelevant with regard to its effect on a particular receiver channel, thereby preventing the pipeline sequence from reaching the final stages. One of three possible categories must be assigned to the packet, as defined below:

- Valid. Packets in this category are considered compatible with the receiver channel and will possibly be accepted and forwarded to other modules in the receiving node, provided that they are not affected by an excessive number of errors. Classification as a valid packet usually depends at least on agreement between transmitter and receiver channels concerning the values of certain key attributes.
- Noise. This classification is used to identify packets whose data content cannot be received, but that have an impact on the receiver channel's performance by generating interference. Packets are generally classified as noise as a result of incompatibilities between the transmitter and receiver channel configurations.

- Ignored. If a transmission is determined to have no effect whatsoever on a receiver channel's state or performance, then it should be identified using this classification. The Simulation Kernel will then discontinue the pipeline execution between the transmitter and receiver channels for this particular transmission (future transmissions between the channels are not prevented).

Stage 4 is transmitter antenna gain. It characterizes the phenomenon of magnification or reduction of the transmitted signal energy in a manner which depends on the direction of the signal path. However, antennas that provide no gain to a transmitted signal in any direction are referred to as isotropic, because they have a perfectly symmetric behaviour with respect to all possible signal paths.

The propagation delay stage is the sixth stage (stage 5) of the radio transceiver pipeline, and is specified by the "propdel model" attribute of the radio transmitter. The purpose of this stage is to calculate the amount of time required for the packet's signal to travel from the radio transmitter to the radio receiver. This result is dependent on the distance between the source and the destination. In addition, the propagation delay result is used in conjunction with the result of the transmission delay stage to compute the time at which the packet completes reception.

The receiver antenna gain stage is the seventh stage of the radio transceiver pipeline. It is the earliest stage associated with the radio receiver rather than the transmitter, being specified by the receiver's "ragain model" attribute. The purpose of the receiver antenna gain stage is to compute the gain provided by the receiver's associated antenna, based on the direction of the vector leading from the receiver to the transmitter or no gain for the isotropic antenna.

The receiver power stage is stage 7 which is specified by the "power model" attribute of the radio receiver. The purpose of this stage is to compute the received power of the arriving packet's signal (in watts). For packets that are classified as valid, the received power result is a key factor in determining the ability of the receiver to correctly capture the information in the packet. For packets that are classified as noise, received power still must usually be evaluated to support calculation of relative strengths of valid and noise packets. In general, the calculation of received power is based on factors such as the power of the transmitter, the distance separating the transmitter and the receiver, the transmission frequency, and transmitter and receiver antenna gains.

The interference noise stage is the ninth stage of the radio transceiver pipeline. The purpose of this stage is to account for the interactions between transmissions that arrive concurrently at the same receiver channel. The Simulation Kernel reserves a Transmission Data Attribute (TDA) for the purpose of storing the current level of noise from all interfering transmissions. This accumulator is maintained only for valid packets (as determined by the channel match stage) because there is generally no need to evaluate link quality for noise packets. The interference noise stage is expected to augment the value of this accumulator in each valid packet by the received power of the interfering packet. When a packet (valid or invalid) completes reception, the simulation Kernel automatically subtracts its received power from the noise accumulator of all valid packets that are still arriving at the channel.

Stage 9 is the background noise which is executed immediately after return of the received power stage. The purpose of this stage is to represent the effect of all noise sources except for other concurrently arriving transmissions which are already accounted for by the interference noise stage. The expected result is the sum of the power (in watts) of other noise sources, measured at the receiver's location and in the receiver channel's band. Normally, the background noise value is later added to other noise sources to compute a total noise level in the signal-to-noise ratio stage.

The purpose of SNR stage (stage 10) is to compute the current average power SNR result for the arriving packet. This calculation is usually based on values obtained during earlier stages, including received power, background noise, and interference noise.

Stage 11 BER derives the probability of bit errors during the past interval of constant SNR. This is not the empirical rate of bit errors, but the expected rate, usually based on the SNR. In general, the bit error rate provided by this stage is also a function of the type of modulation used for the transmitted signal.

The error allocation stage is the thirteenth stage of the radio transceiver pipeline. It estimates the number of bit errors in a packet segment where the bit error probability has been calculated and is constant. This segment might be the entire packet, if no changes in bit error probability occur over the course of the packet's reception. Bit error count estimation is usually based on the bit error probability (obtained from stage 11) and the length of the affected segment.

Stages 9 through 12 of the pipeline are invoked to evaluate a link's performance in response to changes in the signal condition. There is always at least one invocation of stages 10 through 12 to evaluate performance over the full duration of a valid packet. However, an additional invocation will occur for each of these stages (9–12) whenever an interfering packet arrives, to compute new signal conditions.

The error correction stage is the final stage of the pipeline. It determines whether or not the arriving packet can be accepted and forwarded via the channel's corresponding output stream to one of the receiver's neighbouring modules in the destination node. This is usually dependent upon whether the packet has experienced collisions, the result computed in the error allocation stage, and the ability of the receiver to correct the errors affecting the packet. Based on the determination of this stage, the Kernel will either destroy the packet, or allow it to proceed into the destination node.